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HEAT TRANSFER TO BOILING LIQUIDS FROM SURFACES OF SINGLE METAL CRYSTALS OF KNOWN LATTICE ORIENTATION; COPPER - STEARIC ACID SYSTEM

A THESIS

Presented to

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Doctor of Philosophy in the

School of Chemical Engineering

By

Zelvin Levine

May 1956

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HEAT TRANSFER TO BOILING LIQUIDS FROM SURFACES OF SINGLE METAL CRYSTALS OF KNOWN LATTICE ORIENTATION; COPPER - STEARIC ACID SYSTEM

Approved: _____
Thesis Advisor

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Date Approved by Chairman: 5/28/56

To my Mother and Father,
who worked all their lives
to make this possible.

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Zelvin Levine

May, 1956

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ABSTRACT

An experimental study of the effect of surface wetting on boiling heat transfer was conducted for the stearic acid - copper system. This investigation was prompted by the need for reliable experimental data with which to prove or disprove existing theories regarding the effect of wetting.

Previous studies of surface wetting achieved the "wetted" and "non-wetted" condition by one of four methods:

1. Addition of "wetting agents" to the liquid;
2. Coating the solid with a film so as to alter the surface condition;
3. Alternate use of different solid materials with the same liquid;
4. Alternate use of different liquids with the same solid surface.

In the studies undertaken in connection with this project, a method unlike those mentioned above was used to obtain the "wetted"and "non-wetted" conditions. The unique feature of this work is the use of carefully prepared surfaces of copper single crystals of known lattice orientation. Gwathmey (1)[1] and co-workers have shown that different degrees of wettability can be obtained by contacting stearic acid with different crystal planes of copper single crystals.

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[1] Reference numbers refer to the Bibliography.

They found that under certain conditions, stearic acid exhibited a greater wettability on surfaces oriented parallel to the 110 planes[2] than on surfaces oriented parallel to the 100 planes.[2] It is felt that boiling studies of single crystal surfaces making use of this phenomena provide a reliable demonstration of the effect of wetting on the heat transfer coefficient in nucleate boiling of stearic acid.

Two copper single crystals, in the form of cylinders one inch long, one inch in diameter, were obtained for these studies. The orientation was such that one had its flat ends parallel to the 110 planes. The other had flat ends parallel to the 100 planes. The boiling studies were conducted using the flat ends of these crystals as the heating surfaces. The objective of these studies was to demonstrate the effect of wetting by comparing the results obtained from the nucleate boiling of stearic acid on the two single crystal surfaces.

The tendency of stearic acid to undergo thermal decomposition led to the use of a low pressure boiler. The vacuum system used permitted continuous operation at pressures as low as about 10 millimeters mercury, absolute pressure. Basically the apparatus consisted of an electrically heated boiler, in which a crystal surface served as the heating surface. A jacketed copper condenser returned to the boiler all of the vapors, thereby permitting continuous operation. Water boiling in the jacket served as the coolant. A thermal shield

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[2] Miller indices.

system was added to provide control over the leakage of heat from the system. Temperature measurements were made using a Leeds and Northrup type K-2 potentiometer with calibrated copper-constantan thermocouples. A complete description of the apparatus is given in the text of the report.

The experimental procedure followed in these studies can be outlined as follows:

1. Preparation of the sample:
    a. Mechanical polishing;
    b. Electropolishing;
    c. Stearic acid etch treatment;
    d. Installation in crystal holder;
2. Cleaning of the boiler and condenser;
3. Start up; attainment of equilibrium;
4. Experimental run.

Detailed description of the experimental procedure is given in the text of the report.

The results of the preliminary experiments indicated a definite effect of surface wetting. The fact that the observed result was not that which had been anticipated prompted a careful repetition of all phases of the work. The subsequent experiments not only confirmed the previous results but also extended them to a slightly higher range of temperature differences. It was found that for differences in temperature between the fluid and surface less than $70^{\circ}F$, the heat transfer coefficient was higher on the wetted surface

than on the non-wetted surface. At temperature differences greater than approximately 70°F, the non-wetted surface exhibited a significantly higher heat transfer coefficient than the wetted surface for the same difference in temperature.

It was concluded that the reproducible results obtained from these experiments are a reliable demonstration of the effect of surface wetting on nucleate boiling of stearic acid.

The author recommends that similar studies be pursued with iron and nickel crystals, using stearic and other fatty acids. It is further recommended that in spite of the laborious treatments involved, single crystals be considered for other surface effect studies.

CHAPTER I

INTRODUCTION

> . . . But, even though the mechanism of heat should, in fact, turn out to be one of those mysteries of nature that are beyond the reach of human intelligence, this ought by no means to discourage us, or even lessen our ardor, in our attempts to investigate the laws of its operations. . . .
>
> Benjamin Thompson (Count Rumford)
>
> January 1798

It is to the layman perhaps odd that 158 years after Thompson's reading of the above lines, scientific papers are still being written about *the mechanism* of heat and the laws of its operations. During the period since Thompson's pioneering work,[1] thousands of such papers have been written in practically every language known to man. And yet mystery still surrounds the mechanism by which heat energy is transferred. The fact that scientific journals continue to devote space to heat transfer research is in itself ample evidence of the fact that interest in the subject is far from being dead. The fact of the matter is that the spectacular advances of the past decade have motivated greater demand for understanding of the fundamental nature of heat transfer processes. Rockets, jet aircraft, nuclear-power reactors,

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[1] "An Inquiry Concerning The Source Of Heat Which Is Excited By Friction." A paper read before the Royal Society (London).

high temperature chemical process equipment, all present the problem of heat transfer at very high thermal flux. The inherent danger of burnout of a high flux system is offset by the increased capacity which it affords - hence the demand for more basic information about high flux processes.

An understanding of the basic mechanism of boiling heat transfer is important because the boiling process occurs in many cases of high flux heat transfer. In other cases, boiling might be utilized if the mechanism were sufficiently well understood to allow dependable design. This situation has resulted in the appearance of an increasingly large number of scientific papers dealing with the fundamental mechanism of boiling heat transfer. Many of these deal with the effect of those variables which are known to be or suspected of being important. One such variable, the effect of which is obscured by contradictory experimental data, is surface wetting. The need for reliable experimental data with which to prove or disprove existing theories regarding the effect of wetting prompted the undertaking of the experimental studies to be described herein.

Before discussing the specific methods and objectives of this study, a few words regarding previous studies seems appropriate. The effect of surface wetting on boiling heat transfer was recognized as early as 1931 at which time Jakob and Fritz (2) published the first paper on the effect of wetting. Since the publication of this first work, many

others have made contributions aimed at an understanding of wetting. (3, 4, 5, 6, 7, 8, 9, 10, 11) All of the experimental studies to date have achieved the "wetted" and "non-wetted" condition by one of four methods:

1. Addition of "wetting agents" to the liquid;
2. Coating the solid with a film so as to alter the surface condition;
3. Alternate use of different solid materials with the same liquid;
4. Alternate use of different liquids with the same solid surface.

In each of these four methods, the metal-liquid interface for "non-wetting" is completely different from the metal-liquid interface for "wetting" conditions. As a consequence of this, the results of such experiments are surrounded with a considerable amount of uncertainty which can be removed only by repeating the experiment under new conditions. In the studies described in this report, a method unlike those mentioned previously was used to obtain the "wetted" and "non-wetted" conditions. It is felt that these experiments provide a reliable demonstration of the effect of wetting on the heat transfer coefficient in nucleate boiling of stearic acid. Such a demonstration is the objective of this thesis.

With this basic objective in mind, a brief description of the presently accepted mechanism of boiling is in order. Figure 1 represents the sort of data obtained by many

investigators. Generally the boiling process is pictured as occuring by one of two mechanisms: - nucleate boiling, represented by points in region AB of the curve, or film boiling, represented by region CD. Region BC is a transition region, wherein the actual mechanism of boiling is thought to be that resulting when the two mechanisms, nucleate and film boiling, complete with one another for predominance.

As one might infer from the name, nucleate boiling is pictured as that process where vapor bubbles form at distinct "nucleation centers" on the heated surface. With increasing temperature the rate of bubble formation increases. At point B on Figure 1 the so-called "critical heat flux" is reached. The associated temperature difference is called the "critical temperature difference." At this point the rate of bubble formation is of the same order of magnitude as the rate at which bubbles migrate away from the surface. This condition leads to the formation of a vapor film on the surface. In the transition region BC, the film is unstable and alternately forms and breaks away. When the temperature difference reaches that at point C, the surface effectively is blanketed with a vapor film. The mode of heat transfer across the film-covered surface is thought to be that of conduction across the film. This concept is in agreement with the experimental fact that large temperature differences are required for transmission of heat in film boiling. The experimental work reported in this thesis was performed in the region of nucleate boiling; - hence no

further explanation of the film boiling region will be given.

The previously mentioned concept of "nucleation centers" warrants further discussion. The experimental basis of this concept is the fact that one can observe in a boiling liquid that the bubbles appear at certain distinct spots where for some reason conditions are most favorable for bubble formation. As yet a completely satisfactory explanation of these nucleation centers has not appeared. Much work has been devoted to this matter which, of course, must be explained if the mechanism of nucleate boiling is to be understood.

An interesting notion regarding nucleation centers has been suggested by Harrison (12): " . . . The nuclei may be nothing more than cavities or roughness elements in the surface which favor the formation of bubbles, or differing force fields arising from differing atomic lattice orientations at the surface. . . . " The latter suggestion will be mentioned again in this thesis, the results of which lend some support to Harrison's suggested explanation of the nucleation phenomena.

The effect of surface roughness on nucleate boiling has been recognized and studies by a number of authors. In a recent paper, Corty and Foust (13) concluded that the size and shape distribution of roughness elements (of a polycrystalline surface) affect nucleate boiling directly, and not just through their effect in establishing nucleation

centers. They further concluded that the contact angle (which supposedly measures the degree of contact between the liquid and the surface) has an effect on nucleate boiling.

Other authors have shown that the contact angle is not an adequate measurement: in fact, it has been shown that contact angle is itself a function of surface roughness.

Since this thesis deals with the effect of wetting, the terms "wetting" and wettability" ought to be carefully defined. As used herein, a "wet" surface is one on which the liquid is in intimate contact with the surface. The process by which this intimate contact is achieved is referred to as "wetting". Where one liquid has a greater tendency to wet a surface than does another liquid, the first liquid is said to have a higher "wettability" for the given surface. Note that as defined here, wettability is a mutual property of both the specified liquid and the specified surface. Figure 2, taken from Jakob (15), shows three degrees of surface wetting - the angle (measured through the liquid) at which the liquid-vapor interface departs from the surface is the so-called "contact angle". Other authors have used the spreading of a liquid drop as a measure of surface wetting. In either case, a contact angle of zero indicates complete wetting, 180 degrees indicates non-wetting. The inadequacy of this contact angle as a measure of wetting has been discussed by several writers and was confirmed by Woodward (12) during the course of the work described in this thesis. Ray

and Bartell (14) have shown that surface roughness of microscopic size and influence the contact angle.

With the above background description of the boiling process, the specific objectives of this research can now be discussed. As mentioned previously, the basic objective of this project is to provide a reliable demonstration of the effect of wetting on the heat transfer coefficient in nucleate boiling of stearic acid. Such a demonstration is to be carried out by comparing the results obtained from experiments in which identical batches of stearic acid are boiled: one on a wetted copper surface and one on a non-wetted copper surface. The wetted and non-wetted surfaces are to be obtained by using different surfaces of single copper crystals of known lattice orientation. The basis of this approach is the work of Gwathmey, Leidheiser, and Smith (1).

During the course of a long series of experiments with single crystals of various metals, these authors observed that the wettability of copper[2] by stearic acid was different for different crystal surfaces. In particular, they found that under certain conditions stearic acid exhibited a greater wettability on surfaces oriented parallel to the 110 planes than on surfaces oriented parallel to the 100 planes. This experimental result was reported by Gwathmey, et al. without explanation in 1945. The mechanism of this phenomena has since been studied by Kruger (16) who proposed that the preferential wetting was the result of the presence of very

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[2]The same effect was observed for nickel and iron, thereby suggesting a possible future extension of this work.

thin oxide films on the crystal surfaces.

Whether or not this is the true explanation for the preferential wetting, the phenomena is an experimental fact which can be reproduced time after time. This preferential wetting is the method by which the wetted and non-wetted surfaces were achieved for the boiling studies to be reported here.

Of the various possible copper surface orientations, the 100 and 110 planes exhibit the greatest difference in wettability by stearic acid. Two copper single crystals, in the form of cylinders one inch long, one inch in diameter, were obtained for these studies. They were oriented such that one had its flat ends parallel to the 110 planes. The other had flat ends parallel to the 100 planes. For simplicity, they are hereafter referred to as the 110 and 100 crystals, respectively. The orientation of these crystals was checked by X-ray diffraction at The Engineering Experiment Station of the Georgia Institute of Technology. By using the flat ends of these crystals as the heating surfaces in the boiling of stearic acid, the effect of the difference in wetting was observed.

A complete description of the procedures followed and the apparatus used is given elsewhere in this thesis.

CHAPTER II

INSTRUMENTATION AND EQUIPMENT

As initially conceived, the apparatus to be used in these experiments was to be quite simple. The basic components were to be a boiler, in which the single crystal served as the heating surface, and a reflux condensor to prevent loss of the acid from the system. Further thought and investigation indicated that more elaborate additions were needed.

The fact that stearic acid undergoes thermal decomposition at rates which increase rapidly with the boiling temperature brought about the decision to carry out these experiments at as low a pressure as could conveniently be controlled; thus, the need for a vacuum system.

During the planning stages of the project it became apparent that significant loss of heat from the boiler could not be tolerated. It was decided that the adiabatic shield principle could be used to give satisfactory control of heat losses: thus, the introduction of the thermal shield system.

The apparatus as used in these boiling studies was designed and constructed specifically for this project. Basically there are seven groups of equipment which will be described separately. They are as follows:

1. Heater assembly with crystal holder;
2. Boiler;

3. Jacketed reflux condenser;
4. Vacuum apparatus;
5. Thermometric apparatus;
6. Thermal shield system;
7. Power supply system.

Heater Assembly with Crystal Holder.--The need for frequent interchange of the various metal samples dictated a design in which the heater itself could be moved from its usual position underneath the boiler. A heater assembly into which a removable crystal holder could be placed was constructed. The heater consists of a solid copper core, insulated with Sauereisen cement, and wound with a Nichrome wire resistance heater designed for a maximum power output of 150 watts. As shown in Figure 15, the heater assembly (which is made up of the heater core and its baseplate, the crystal holder, and the tie rods and flanges) is fastened to the boiler tube by three tie rods. The adjustment of the upper set of tie rod nuts allows the heater to be brought into close contact with the bottom of the crystal. The installation of the entire assembly is shown in Figure 13. The heater core is surrounded by two small concentric copper tubes which serve to minimize the heat loss from the heater core. The electrical leads are Number 18 gauge asbestos-insulated copper wire. The flanges are made of brass; tie rods and nuts of steel. A small hole is drilled into one side of the heater core to permit insertion of an iron-constantan thermocouple with which to measure the core temper-

ature. This temperature is for control purposes only; hence the location of the thermocouple is not critical.

The crystal holder is made of brass. Its sealing action is that of a packing gland - the packing being ordinary asbestos cord. (See Figure 16).

Boiler.--The boiler itself is a standard section of tempered Pyrex pipe, 1 inch inside diameter, 6 inches long. As shown in Figure 15, the boiler pipe is fastened to the heater assembly by the three tie rods. A Teflon gasket serves to seal the joint and at the same time thermally insulate the pipe from the crystal holder. The boiler is wrapped with a nichrome resistance heater which can be used to melt the charge of stearic acid. When operating at very low power levels the power of this heater can be adjusted to compensate for heat loss to the surroundings.

Jacketed Reflux Condenser.--This condenser, shown in Figure 14, is made of two concentric copper tubes, the outer annulus serving as a water boiler. The jacket is fitted with flare fittings so as to permit operation with circulating cooling water if desired. The system operates at total reflux; condensed stearic acid flows under the influence of gravity down the walls into the boiler. Operation of the condenser as a water boiler eliminates any possibility of solidification of stearic acid on the condenser walls, a condition which caused operational difficulties during a test run in which circulating cooling water was forced through the condenser jacket. In normal operation the water in the jacket boils

away gradually. Additions are made once or twice each day of operation. A nichrome resistance heater is wound around the outside of the condenser jacket for initial heating of the water in start-up. The condenser is vertical, positioned concentrically with respect to the longitudinal axis of the boilers. The condenser is mounted securely in the test site and need never be disconnected at any time during the runs. The boiler and heater assemblies are lifted up into place and suspended from the condenser baseplate by three bolts. A Teflon gasket provides the sealing action. (See Figure 14.)

Vacuum Apparatus.--The vacuum system used in this work consists of a Cenco Hyvac pump, a cartesian manostat, a mercury absolute pressure manometer, two traps, two glass stopcocks, and two diaphragm valves. Installation is as shown in Figure 13. This simple vacuum system was found to be quite adequate for continuous operation at pressures down to about 10 millimeters mercury, absolute pressure.

Thermometric System.--Temperatures were measured with a Leeds and Northrup K-2 potentiometer with an optical beam moving coil galvanometer. Number 30 gauge copper-constantan paired thermocouple wire from a single spool was used throughout all the runs; calibration for accuracy of 0.5F was made using a standard platinum - platimum 10% rhodium thermocouple.

Thermal Shield System.--As shown in Figure 18 the entire heater assembly is surrounded by two large concentric copper shields. The outer shield is wrapped with an auxiliary Nichrome resistance heater. A copper-constantan difference

thermocouple serves to indicate the temperature difference between the two shields. The indicating system is as shown in Figure 18. During start-up both knife switches are open. The setting of the auxiliary Powerstat is adjusted so as to maintain zero temperature difference, as indicated by zero current through the galvanometer. As the thermal shields approach equilibrium, the protective resistances of the two rheostats are gradually removed from the circuit, first by adjustment of the 10,000 ohm rheostat, then by closing switch Number 2 to remove the residual resistance of the 10,000 ohm rheostat. For ultimate sensitivity in the indicating system, the setting of the 100 ohm rheostat is gradually adjusted to lower resistances. Finally knife switch Number 1 is closed, leaving only the galvanometer in series with the difference thermocouple. In this case the full unbalanced electromotive force of the thermocouple is applied to the galvanometer. The efficiency of the thermal shield system was determined by a test run in which the temperature rise of circulating condenser cooling water was measured to permit a check on the heat loss from the system. These checks indicated a heat loss of less than 10 per cent, a figure which was considered satisfactory in view of the fact that the error so introduced is the same regardless of which metal sample is in use.

Power Supply System.--A conventional 0-270 volt Powerstat (variable transformer) was used to supply the power for resistance heating of the main heater. The circuit is shown in detail in Figure 17. An ammeter and a voltmeter are

installed on the control panel (Figure 19) for control purposes only. A calibrated high precision Weston A.C. Wattmeter, Model number 310, was used for measurement of the power supplied to the heater.

CHAPTER III

PROCEDURE

The experimental procedure followed in these studies consists of four distinct steps, as follows:

1. Preparation of the sample;
2. Cleaning of the boiler and condenser;
3. Start-up;
4. Experimental run.

These four steps will be described separately in the following pages.

Preparation of the Sample

In such a case as this where the effect of surface condition is being studied, it is self-evident that preparation of the sample surface is extremely important. The procedure followed in this work is based on the sample preparation described by Gwathmey, whose work (1) with single crystals is the very foundation of this study. The sample preparation itself consists of four steps which were carefully followed time after time to assure reproducibility of the final surface state.

Mechanical Polishing.--The single crystal samples used throughout this study were supplied by the Virginia Institute for Scientific Research.[1]

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[1] Virginia Institute for Scientific Research
326 North Boulevard, Richmond, Virginia

They required no further machine work other than the drilling of the thermocouple holes. Following the completion of this operation, the samples were given a so-called mechanical polish in which the sample was polished by hand on a flat surface using emery finishing paper. The mechanical polish was considered adequate when only very faint scratches could be seen after polishing on grade 0000 paper, the finest grade abrasive paper available. At this point the sample surface had nearly a mirror finish. Mechanically polishing to this condition assures that the next step, electro-plishing, will always start at the same surface condition. (Later studies showed this to be unnecessary, but nevertheless this step was included in all of the work).

Electro-polishing.--The electro-polishing step is included in the sample preparation to provide a surface free from mechanical strain. At the same time, electro-polishing removes the extremely fine deposits of randomly oriented granules which are smeared across the surface in the mechanical polishing step. The technique used is that of Jacquet (17), as adopted by Woodward (12) for this project. The polishing was carried out in a 250 milliliter beaker. The sample being polished was made the anode at the bottom of the cell; the surface to be polished was horizontal, 1 inch above the bottom of the beaker. A flat plate of copper serving as the cathode was suspended 1 inch above and parallel to the surface being polished. The electrolyte was 65 per cent by weight $H_3 PO_4$; 200 milliliters of fresh solution were used for each polishing

operation. A 6 volt wet cell battery supplied the D. C. current. A 25 ohm rheostat, an ordinary double pole knife switch, a 3 ampere D. C. ammeter, a 5 volt D. C. Voltmeter, and the required lead wires completed the simple circuit for direct current polishing.

Although no attempt was made to achieve anything near perfection in the electro-polishing step, the following technique resulted in an excellent mirror-like finish. After installing the sample in the cell and completing all connections, the electrolyte was poured into the cell. Any air bubbles formed on the surface were removed with a cotton-tipped swab. The cathode was then put in place and the switch closed to start the polishing operation. During the first several minutes, frequent changes in the rheostat setting were needed to maintain the voltage at 1.8 to 1.9 volts; however, after about five minutes, the system became more stable and thereafter the rheostat required only occasional adjustment to maintain a constant voltage of 1.8 to 1.9 volts across the cell. (Although no attempt was made to control the polishing current, it generally leveled off around 1.5 amperes after the first few minutes of the polishing operation. The initial current, when the switch was first closed, was generally 2.4 to 2.6 amperes.) After 30 minutes of polishing, no further improvement in the quality of the finish was observed. Polishing was terminated at the end of 30 minutes, at which time the sample was thoroughly washed in water, followed by an alcohol wash, then dried by wiping with clean cotton. The

110 sample gave a beautiful mirror-like finish; the others were likewise mirror-like, although the 100 sample surface had a few pitted spots, apparently due to gas bubbles in the original melt from which the crystal was grown.

Stearic Acid Etch Treatment.--As reported by Gwathmey (1), the desired preferential wetting effect is obtained only after a "conditioning" treatment which apparently affects both the metal surface and the stearic acid. The "conditioning" treatment consists of alternately exposing the surface to hot stearic acid and air. For this treatment, a mechanical dunking device consisting of a motor and a small gear-box was used. A pin mounted near the outer edge of a pulley on the low speed shaft of the gear box provided the oscillatory motion to alternately lower and raise (20 times per minute) the three samples (the two single crystals and a polycrystal) which were suspended in the molten stearic acid by an asbestos cord. The samples themselves were clamped around their cylindrical surfaces such that the flat surfaces moved up and down in a vertical plane. The stearic acid both was maintained at the desired temperature of 180-200°C with a thermostated electric hot plate. A single batch of stearic acid, so treated, was used in all the boiling studies. Although no attempt has been made to determine the exact nature and amount of decomposition occuring in the acid during this treatment, it is known that the acid does undergo some thermal decomposition with resultant formation of ketones. The obtained data, therefore, are not necessarily those of "pure" stearic acid

(if such a thing as a "pure" fatty acid even exists) but rather those of an acid contaminated with various decomposition products. Again, however, any error introduced by small variations in composition are present no matter which sample is being studied.

After approximately 4 hours of dunking, a very dramatic difference in what is here called "wettability" of the surfaces is observed. As the samples are pulled out of the bath by the cord, the liquid film on the surface of the 100 sample pulls away from the surface and rushes toward the upper and lower edges. It appears that two small waves form out of the viscous acid film on the surface; one wave retreats vertically up the surface, against the force of gravity; the other runs down the surface considerably faster than do the falling films on the 110 sample or the polycrystalline sample. On these latter two samples, ordinarily both surfaces remain wetted. Although the viscous film flows down the vertical faces under the influence of gravity, there is generally no dramatic break-away of the film as in the case of the 100 sample. At times even these samples exhibit the non-wetting effect for a short time. On continued dunking, however, the phenomena vanishes. On the 100 sample this effect has been maintained for several days, at which time the experiment was finally stopped and the sample left immersed in the acid where it remained several days in cold, solidified acid. On remelting the acid, the non-wetting effect recurred the very first time the sample was lifted from the acid bath.

After attainment of the desired preferential wetting effect, the dunking operation was stopped and the samples lowered into the acid bath. When the liquid was just above the solidification temperature of 129°C, the sample desired was lifted out. Because of the viscous nature of the acid near its solidification temperature, the sample was covered with a thick film which on cooling to room temperature produced a green coating resembling cheese mold. This coating was wiped off of all but the flat sample surface which was to be studied. Leaving this coating in place prevents any further air oxidation; furthermore, any accidental damage to the surface during subsequent handling will be revealed by damage to this green coating. The sample was then ready to be installed in the crystal holder.

Installation in the Crystal Holder.--The principal objective of the procedure used for installing the sample is to avoid any damage to the surface condition achieved in the etch treatment. The sample was carefully inserted into the holder so as to line up the thermocouple hole in the sample with the corresponding hole in the body of the crystal holder. With the holes lined up, a steel pin slightly smaller than the thermocouple tube was inserted to keep the crystal in place during the packing step.

As shown in Figure 15 the sealing action in the crystal holder was provided by the compression of an asbestos packing. Ordinary asbestos cord was used to make this packing which generally was replaced each time a new sample was installed

in the holder. The formation of the packing was quite simple: about 5 or 6 turns of 1/8 inch cord were wound around the sample, the holder having been clamped on the two flat surfaces in a vise. After winding on the cord, the inner piece of the crystal holder was screwed in place and tightened with an adjustable end wrench. Examination of a packing prepared in this manner showed that the compression resulted in a large increase in the density of the asbestos, which is ordinarily a light, fibrous material. The steel pin was then removed and the thermocouple tube (a soft nickel alloy tube, welded shut at one end) carefully forced into place. The installation of the sample having been completed, the entire holder was then placed in the heater assembly, the bottom of the sample resting directly on top of the heater core, as shown in Figure 15. The crystal-temperature thermocouple was then inserted into the tube.

Cleaning of the Boiler and Condenser

During the time that each sample was being prepared, the boiler and condenser were cleaned of stearic acid deposits by boiling out the system with an organic solvent, generally ethyl alcohol. Occasionally the system was boiled a second time with benzene to remove any undissolved residue remaining on the condenser walls. For these boiling operations, a polycrystalline copper sample was used as the heated surface. Like some of the steps included in the sample preparation, this regular cleaning of the boiler and condenser was another routine operation which may or may not have been necessary,

but which, nevertheless, was included as an added precaution to maintain reproducibility of the experimental conditions.

Start-up; Attainment of Equilibrium

After completion of the previous two steps, at which point the prepared sample, in its holder, had been placed in the heater assembly, the cleaned boiler was fastened in place on top of the heater assembly by tightening the three nuts on the tie rods. The acid from the previous sample conditioning step was then poured in, after melting on the hot plate. A five inch head of liquid was used in all runs. Following the addition of the liquid, the boiler was raised in place up to the condenser baseplate and the closure affected by tightening the three bolts. After a routine check of all bolts for tightness, the system was ready for start-up.

To minimize the time required for the start-up operation, the main heater was set at a high power level, generally 120 watts. At the same time the warming heater which surrounds the boiler tube was turned on at approximately 30 watts. While the acid was heating, the heater surrounding the condenser jacket was turned on to bring the condenser water up to the boiling point. When the acid temperature reached approximately 250°F, the vacuum pump was turned on and the manostat adjusted to give the desired pressure.

After reaching the pressure sought, the system was tested for leakage by temporarily closing the straight-through glass stopcock. Excessive leakage was indicated by a rapid rise in the pressure within the system. The most common cause

of leakage was found to be the slow relaxation under continued heating of the asbestos impregnated neoprene pads which separate the Pyrex boiler tube from the metal flanges. To offset this effect, the nuts on the tie rods and bolts were tightened periodically. Following the leak test, the thermal shields were lifted into position and the space above them loosely packed with pads of Fiberglas insulation. With the pressure under control and the shields in place, the power level of the main heater then was adjusted to a setting in the usual operating range (generally 20 to 100 watts), and the warming heater turned off. Because of the inherent self-regulating nature of the condenser-boiler, the system was often left unmanned for several hours to allow attainment of equilibrium.

The matter of determining whether or not equilibrium had been reached was a difficult and, of course, important problem. Once the liquid reached the saturation temperature corresponding to the maintained pressure, the liquid temperature remained essentially constant. On the other hand, the crystal temperature, as measured by the sub-surface thermocouple, approached its ultimate steady-state temperature at a steadily decreasing rate; the temperature gradually rose or gradually fell depending on whether it was previously at a lower or higher temperature. For this study a crystal temperature was considered to be sufficiently close to the steady-state value when two readings taken not less than thirty minutes apart indicated a difference of one degree or less; since

each individual temperature was accurate only within one-half degree fahrenheit, the error so introduced is allowable.

Experimental Run

When the system had reached equilibrium at the initial power level, equilibrium being determined as mentioned above, a single reading was taken for the particular sample at the pressure being maintained. A complete experimental run consists of such points at all power levels. For all practical purposes, however, the operating range is bounded: above, by the critical heat flux at which burn-out occurs; below, by the difficulty of maintaining boiling at very low power levels where heat losses become significant. The practical limits of this system are approximately 100 watts and 20 watts, although some points were obtained outside of these limits. (Inevitably, some burn-outs occurred also; a fluctuation in pressure when operating at powers above 100 watts caused burnout on two occasions. The critical heat flux apparently near 125 watts for 17mm absolute pressure.) After recording the data taken at the initial setting, the power level was altered by adjusting the Powerstat. The temperature of the crystal surface changed immediately; as mentioned before, however, the rate at which this temperature approached the new limit decreased steadily. Accompanying the change in crystal temperature was, naturally, a change in the entire spacial temperature distribution within the heater assembly. This, in turn, resulted in a change in the temperature of the

inner thermal shield. To maintain the condition of minimum heat interchange between the two thermal shields, the power input to the auxiliary (shield) heater had to be adjusted. After some experimentation it was found that the required setting of the auxiliary heater Powerstat could be predicted for each setting of the main heater Powerstat. This had been expected but no attempt was made to set down the actual correlation between the two settings because of the ease with which the auxiliary Powerstat setting could be determined, and because of the fact that the auxiliary Powerstat setting varied slightly with room temperature, airflow across the laboratory, etc. In practice, the usual procedure was to set the auxiliary Powerstat at the approximate setting corresponding to the new power level of the main heater. Until the crystal temperature was near its limiting value, the rheostats in the shield circuit were kept at their maximum resistance settings. When near equilibrium, the auxiliary Powerstat was given a fine adjustment so as to balance the shield circuit galvanometer. The ultimate balance was obtained when knife switch Number 1 was closed, in which case the entire thermal current of the difference thermocouple passed through the galvenometer. With the shield circuit balanced at the new power level and the crystal temperature nearly constant, another datum point was recorded. The above process of changing power was then repeated. In this manner the required data were obtained. Generally a run was considered completed when a reading had been made twice at each of about six power

levels, once approaching the point from a lower level, once from a higher level. This technique was designed to avoid "false equilibrium".

In order to extend the range of the data, it was found desirable to go to as low a power as possible. As mentioned before, however, heat losses become significant at powers of 10 watts and less. To get data in this range where the boiling process is probably little more than natural convection with the formation of an occasional bubble, a special technique was developed. Basically this technique was a method of compensating for the small amount of heat lost by the boiler through the Fiberglas insulation above the thermal shields. The warming heater which surrounds the boiler tube was turned on at a low power, generally about 10 watts initially. After equilibration, a reading was taken and the warming heater power was reduced slightly. After equilibrium, another reading was taken. This process of successively lowering the warming heater power by small increments was repeated until a level was reached at which the power input did not compensate for the heat losses, in which case the liquid stopped boiling and cooled below its saturation temperature. In this manner the correct setting of the warming heater Powerstat corresponding to the power of the main heater was determined. Experimentally it was found that the ultimate crystal surface temperature was essentially independent of small changes in warming heater setting provided the setting was very near the correct value. With

this technique, points were obtained at power levels as low as 6 watts.

One additional point worthy of mention in this record is the fact that the boiling temperature of the acid at the maintained pressure underwent a change of as much as 3 degrees Fahrenheit during the course of a run, which often took two or three days. Fortunately, however, this slight drift in the liquid's boiling temperature was found to be insignificant. This was established by the cyclic method of operation: readings were taken first with increasing power, then with decreasing power. Experimental measurements made as much as three days apart at the same power level were found to be in good agreement. This was interpeted as a confirmation of the hypothesis that minor changes in the liquid composition, as indicated by a drift in the boiling temperature, should have little effect.

Upon completion of an experimental run, the power to all heaters was turned off. After the system had cooled for a short time the vacuum pump was turned off and air admitted to the system, which could then be left unmanned. When all parts were cooled to room temperature, the insulation about the boiler was removed and the shields lowered out of their usual place around the heater assembly. After removing the crystal holder and the thermocouple, the thermocouple tube was withdrawn by gripping it with a pair of pliers. (To prevent collapsing of the tube walls, a wire was inserted into the open end of the tube). After removing the tube, the holder was clamped in a vise and dismantled to remove

the sample. The asbestos packing generally was discarded before another sample was installed.

CHAPTER IV

DISCUSSION OF RESULTS

Preliminary experiments on the two copper single crystals indicated that the principal objective of the project would be fulfilled. That is, the preliminary results demonstrated a definite effect due to wetting. The effect was not exactly that which had been anticipated, but rather was one which, on further thought, one might have anticipated.

The preliminary work indicated that for differences in temperature between the fluid and surface less than 70°F, the heat transfer coefficient was higher on the wetted surface than on the non-wetted surface. However, at temperature differences greater than approximately 70°F, the non-wetted surface exhibited a significantly higher heat transfer coefficient than the non-wetted surface for the same difference in temperature. In as much as such a result has never been reported in the literature, the result was viewed with suspicion.[1] To insure a rigid test of the reproducibility of this work, the crystals were given the entire treatment: mechanical polishing, electro-polishing, and stearic-acid conditioning (as described in Chapter III) before repeating

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[1] Although new experimental results warrant closer scrutiny than might otherwise be the case, it is the writer's opinion that the careful repetion of all phases of the experiments established the reproducibility of the work.

the heat transfer experiments. The subsequent experiments not only confirmed the previous results but also extended them to a slightly higher range of temperature differences. The experimental data are summarized in Tables 1 and 2 and plotted in Figure 21. As mentioned above, such an intersection of the superimposed graphs was not expected. However, a plausible explanation for this effect has been suggested. At low heat fluxes, where the temperature difference is small, and bubble formation almost negligible, the mechanism of heat transfer is perhaps that of natural convection. In this range, a non-wetted condition at the surface would probably add resistance to the transfer of heat from the surface to the fluid. The results shown in Figure 21 are consistant with this hypothesis. With increasing temperature difference, the rate of bubble formation should increase rapidly. If, however, the rate of bubble formation were greater for the non-wetted surface than for the wetted surface,[2] it is quite likely that there might exist a temperature difference beyond which the greater rate of bubble formation would cause the heat transfer coefficient to be greater for the non-wetted surface. Furthermore, if one concedes that the difference in wettability might increase with an increase in the temperature difference, then it is all the more probable that the non-wetted surface might exhibit better heat transfer than the wetted surface.

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[2] Larson (18) states that this might be the case. Proof of this for the copper-stearic acid system would require a complete understanding of the intermolecular force fields at the metal-fluid interface.

This effect has been demonstrated experimentally in this work. Proof of the explanation described above cannot be extracted from these experiments alone. Perhaps future studies will provide further understanding of the experimental facts reported here.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

From this work, which was planned and executed as a purely experimental one, the results summarized in Tables 1 and 2 and presented in Figure 21 constitute the desired conclusion. These data can be summarized in the following statement: an effect of surface wetting on the heat transfer coefficient in nucleate boiling of stearic acid on surfaces of single copper crystals has been demonstrated. The results obtained with this somewhat unusual system, copper - stearic acid, cannot be considered sufficiently general to enable one to apply them to all substances. In fact, it is because of the peculiar preferential wetting effect that this system was studied in the first place. If the results here reported serve to stimulate more study of the effect of wetting, they will have served a worthy purpose.

It is recommended that similar studies be pursued with iron and nickel crystals, using stearic and other fatty acids.

It is further recommended that in spite of the laborious treatments involved, single crystals be considered for other surface effect studies.

APPENDIX

Table 1. Summary of Data for 100 Sample

$q/A \times 10^{-3}$	h	t
8.06	139	58
	144	56
8.64	149	58
	144	60
	149	58
11.5	183	63
23.0	261	88
	256	90
24.2	278	87
	288	84
32.2	316	102
	319	102
33.4	334	100
	327	102
46.1	435	106
	419	110
	435	106
57.6	480	120
	488	118
	484	119
	480	120
63.3	510	124

q/A = heat flux, BTU/hr.ft.^{2}

h = heat transfer coefficient, BTU/hr.ft.^{2}°F.

t = temperature difference between surface and fluid, degrees Fahrenheit.

Table 2. Summary of Data for 110 Sample

$q/A \times 10^{-3}$	h	t
3.45	91	38
5.47	119	46
	127	43
8.64	146	59
	154	56
9.21	162	57
	154	60
	171	54
11.5	192	60
	185	62
	180	64
14.4	195	74
	206	70
16.7	226	74
	220	76
17.3	216	80
	222	78
	234	74
	231	75
	228	76
20.7	246	84
	244	85
25.3	281	90

Continued next page.

q/A = heat flux, BTU/hr.ft.^{2}

h = heat transfer coefficient, BTU/hr.ft.^{2}^{o}F.

t = temperature difference between surface and fluid, degrees Fahrenheit.

Table 2. Summary of Data for 110 Sample, continued.

$q/A \times 10^{-3}$	h	t
25.9	288	90
28.2	276	102
35.7	308	116
	310	115
43.8	350	125
49.2	370	132
	373	132
49.5	375	132
	399	124

q/A = heat flux, BTU/hr.ft.^{2}

h = heat transfer coefficient. BTU/hr.ft.^{2} °F.

t = temperature difference between surface and fluid, degrees Fahrenheit.

Table 3. Experimental Data for 100 Sample

Nomenclature:

V_s = Voltage setting of shield system Powerstat.

V_w = Voltage setting of warming heater Powerstat.

E_c = Millivolt reading of core thermocouple.

E_4 = Millivolt reading of surface thermocouple.

E_5 = Millivolt reading of fluid thermocouple.

t_4 = Temperature corresponding to reading of surface thermocouple, degrees Fahrenheit.

t_s = True surface temperature, corrected for location of junction below surface, degrees Fahrenheit.

t_1 = Temperature of fluid, degrees Fahrenheit.

t = Difference in temperature between surface and fluid, degrees Fahrenheit.

q/A = Heat Flux, BTU/hr.ft.^{2}

h = Heat transfer coefficient, BTU/hr.ft.^{2}°F. $= \frac{q/A}{t}$

P = Absolute pressure in system, millimeters of mercury.

Continued on next page.

Table 3. Experimental Data for 100 Sample, continued.

Date: July 21-23, 1955

Time	Power, Watts	V_s	E_c	E_4	E_5	t_4	t_s	t_1	t	q/A x10^{-3}	h	P	V_w
July21													
11:20	40												
1:15	40	100	19.7	14.23	11.44	552.5	551	463.5	88	23.0	261	17	0
1:40	40	94	19.7	14.33	11.50	555.5	554	465.5	88	23.0	261	17	0
1:40	80												
1:55	80	101	23.0	14.91	11.50	573.5	570	465.5	104	46.1	443	17	0
2:00	80	102	23.1	14.95	11.50	574.5	572	465.5	106	46.1	435	17	0
2:05	80	103	23.3	15.05	11.50	578.0	576	465.5	110	46.1	419	17	0
2:05	100												
2:17	100	109	25.1	15.14	11.50	583.5	580	465.5	114	57.6	505	17	0
2:25	100	109	25.7	15.27	11.45	584.5	581	463.5	118	57.6	488	17	0
2:33	100	109	25.9	15.34	11.45	586.5	583	463.5	120	57.6	480	17	0
2:33	110												
2:38	110	111	26.5	15.42	11.45	589.0	586	463.5	124	63.3	510	17	0
2:41	110	111	26.7	15.48	11.45	591.0	587	463.5	124	63.3	510	17	0
2:41	58												
3:12	58	98	22.7	14.82	11.50	570.5	568	465.5	102	33.4	327	17	0
3:26	58	100	22.4	14.70	11.50	567.0	565	465.5	100	33.4	334	17	0
July22													
4:50	42	91	20.0	14.28	11.57	554.0	552	467.5	84	24.2	288	17	0
5:03	42	91	20.1	14.36	11.58	556.5	555	468.0	87	24.2	278	17	0
July23													
9:30	20	87	17.5	13.68	11.67	535.0	534	471.0	63	11.5	183	17	0
9:30	14												
1:15	14	82	16.7	13.47	11.66	528.5	528	470.5	58	8.06	139	17	0
1:28	14	80	16.7	13.46	11.70	528.0	528	472.0	56	8.06	144	17	0

Table 3. Experimental Data for 100 Sample, continued.

Date: September 13-15, 1955

Time	Power, Watts	V_s	E_c	E_4	E_5	t_4	t_s	t_1	t	q/A x10^{-3}	h	P	V_w
September 13													
2:30	40												
4:40	40	90	20.1	14.30	11.50	554.5	553	465.5	88	23.0	261	17	0
8:10	40	91	20.2	14.32	11.50	555.0	554	465.5	88	23.0	261	17	0
9:05	40	91	20.2	14.37	11.50	556.5	555	465.5	90	23.0	256	17	0
9:05	15												10
September 14													
11:40	15	82	16.4	13.42	11.58	527.0	526	468.0	58	8.64	149	17	10
11:55	15	82	16.4	13.43	11.59	527.0	526	468.0	58	8.64	149	17	10
1:20	15	82	16.4	13.47	11.60	528.5	528	468.5	60	8.64	144	17	10
3:10	15	82	16.5	13.48	11.65	529.0	528	470.0	58	8.64	149	17	20
3:10	55												
8:05	56	102	22.7	14.76	11.50	569.0	567	465.5	102	32.2	316	17	0
9:15	56.5	103	22.8	14.76	11.50	569.0	567	465.5	102	32.5	319	17	0
September 15													
8:50	80												
10:40	80	105	23.5	14.94	11.50	574.5	572	465.5	106	46.1	435	17	0
10:52	80	105	23.6	14.97	11.50	575.0	572	465.5	106	46.1	435	17	0
11:03	80	106	23.7	15.04	11.50	577.5	575	465.5	110	46.1	419	17	0
11:10	80	106	23.7	15.06	11.50	578.0	575	465.5	110	46.1	419	17	0

Table 4. Experimental Data for 110 Sample

Nomenclature:

V_s = Voltage setting of shield system Powerstat.

V_w = Voltage setting of warming heater Powerstat.

E_c = Millivolt reading of core thermocouple.

E_4 = Millivolt reading of surface thermocouple.

E_5 = Millivolt reading of fluid thermocouple.

t_4 = Temperature corresponding to reading of Surface thermocouple, degrees Fahrenheit.

t_s = True surface temperature, corrected for location of junction below surface, degrees Fahrenheit.

t = Difference in temperature between surface and fluid, degrees Fahrenheit.

q/A = Heat flux, BTU/hr. $ft.^2$

h = Heat transfer coefficient, BTU/hr.$ft.^2{}^oF. = \frac{q/A}{t}$

P = Absolute pressure in system, millimeters of mercury.

Continued on next page.

Table 4. Experimental Data for 110 Sample, continued.

Date: July 26-27, 1955

Time	Power, Watts	V_s	E_c	E_4	E_5	t_4	t_s	t_1	t	q/A x10^{-3}	h	P	V_w
July26													
9:55	76												
10:21	76	110	25.5	15.36	11.38	587.5	585	461.5	124	43.8	350	17	0
10:35	76	108	25.5	15.38	11.34	588.0	585	460.0	125	43.8	350	17	0
10:35	86												
10:45	86	110	26.2	15.49	11.34	591.5	588	460.0	128	49.5	387	17	0
10:55	86	110	26.5	15.59	11.30	594.5	592	459.0	132	49.5	375	17	0
2:26	86	111	26.3	15.32	11.34	586.0	583	460.0	123	49.5	402	17	0
2:28	86	111	26.4	15.36	11.34	587.5	584	460.0	124	49.5	399	17	0
2:32	86	111	26.5	15.38	11.34	588.0	585	460.0	125	49.5	396	17	0
2:37	62												
2:50	62	107	24.5	15.08	11.32	578.5	576	459.5	118	35.7	303	17	0
2:58	62	108	24.5	15.05	11.32	578.0	576	459.5	116	35.7	308	17	0
3:05	62	108	24.4	15.04	11.33	577.5	575	460.0	115	35.7	310	17	0
3:10	44												
6:45	44	98	21.5	14.20	11.35	551.5	550	460.5	90	25.3	281	17	0
7:05	44	99	21.5	14.16	11.35	550.0	548	460.5	88	25.3	288	17	0
7:05	36												
8:48	36	92	20.3	13.96	11.28	544.0	543	458.0	86	20.7	244	17	0
8:55	36	94	20.3	13.93	11.29	543.0	542	458.5	84	20.7	246	17	0
8:55	30												
9:15	30	92	19.7	13.80	11.26	539.0	538	457.5	80	17.3	216	17	0
9:48	30	92	19.3	13.73	11.25	536.5	535	457.0	78	17.3	222	17	0
9:48	25												
10:35	25	90	18.7	13.54	11.21	530.5	530	456.0	74	14.4	195	17	15
10:42	25	90	18.7	13.50	11.28	529.5	528	458.0	70	14.4	206	17	25
July27													
9:30	20	90											80
10:27	20	92	17.3	13.29	11.38	523.0	522	461.5	60	11.5	192	17	80

Continued next page.....

Table 4. Experimental Data for 110 Sample, continued.

Time	Power, Watts	V_s	E_c	E_4	E_5	t_4	t_s	t_1	t	q/A x10^{-3}	h	P	V_w
July27, continued.													
10:40	20	90	17.3	13.33	11.38	524.0	523	461.5	62	11.5	185	17	80
11:03	20	90	17.3	13.36	11.38	525.0	524	461.5	62	11.5	185	17	40
11:58	20	89	17.5	13.38	11.36	525.5	525	461.0	64	11.5	180	17	30
11:58	16												30
1:14	16	88	16.7	13.21	11.40	520.0	519	462.0	57	9.21	162	17	30
1:23	16	88	16.5	13.19	11.32	519.5	519	459.5	60	9.21	154	17	25
2:23	16	88	16.5	13.16	11.45	518.5	518	464.0	54	9.21	171	17	35
2:40	9.5	84	15.7										35
3:40	9.5	84	15.7	12.81	11.37	507.5	507	461.0	46	5.47	119	17	35
3:50	9.5	84	15.7	12.81	11.45	507.5	507	464.0	43	5.47	127	17	35
3:50	6.0												40
4:22	6.0	80	15.0	12.63	11.48	502.0	502	464.5	38	3.45	91	17	40
5:00	6.0	79	14.9	12.47	11.30	496.5	496	458.5	38	3.45	91	17	35
5:00	29												35
8:25	29	90	19.1	13.85	11.52	540.5	540	466.0	74	16.7	226	17	35
8:30	29	90										17	0
8:55	29	92	19.1	13.84	11.47	540.0	539	464.5	74	16.7	226	17	0
9:15	29	92	19.1	13.79	11.40	538.5	538	462.0	76	16.7	220	17	0

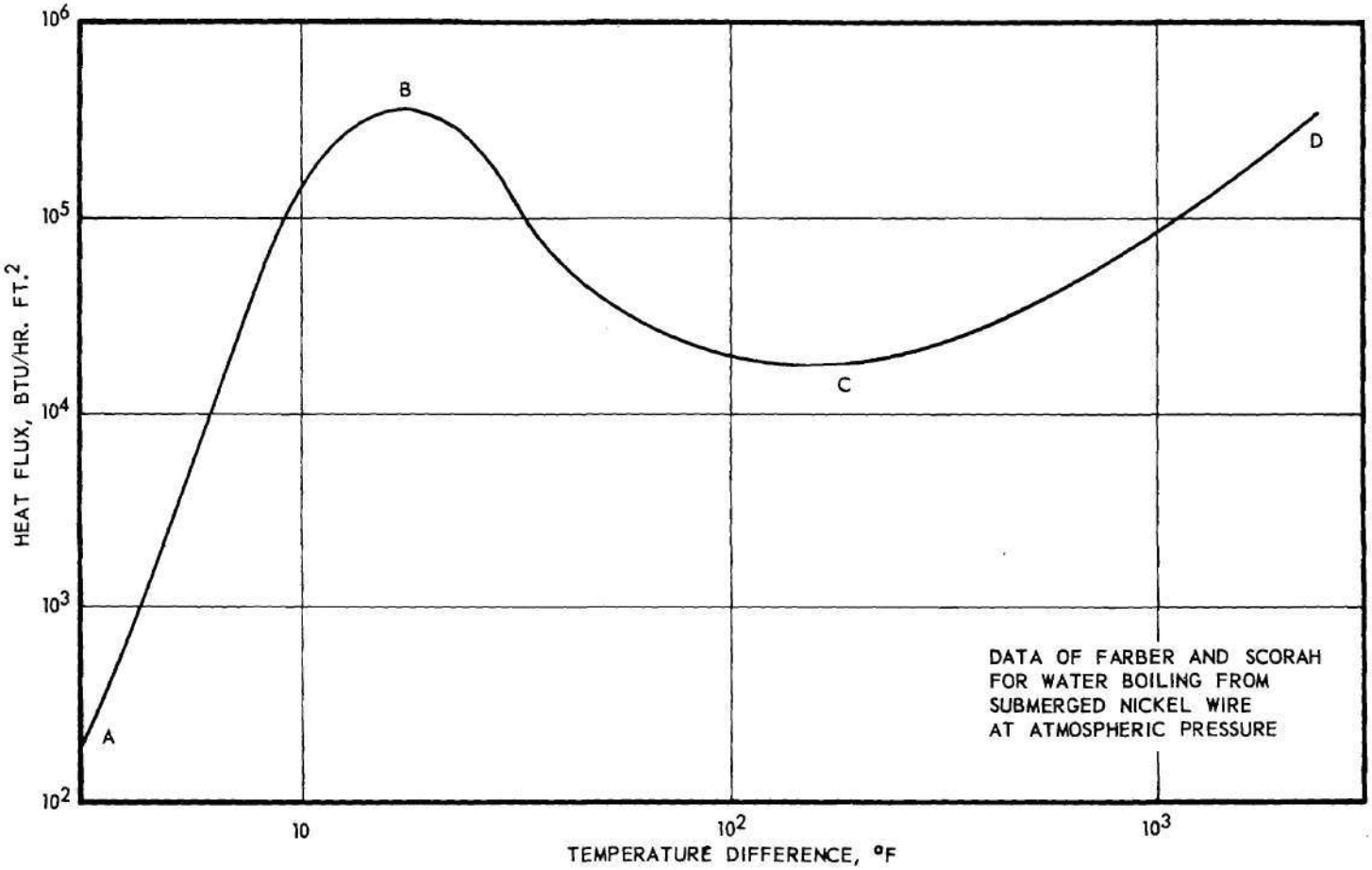


Figure 1. Typical Boiling Data.

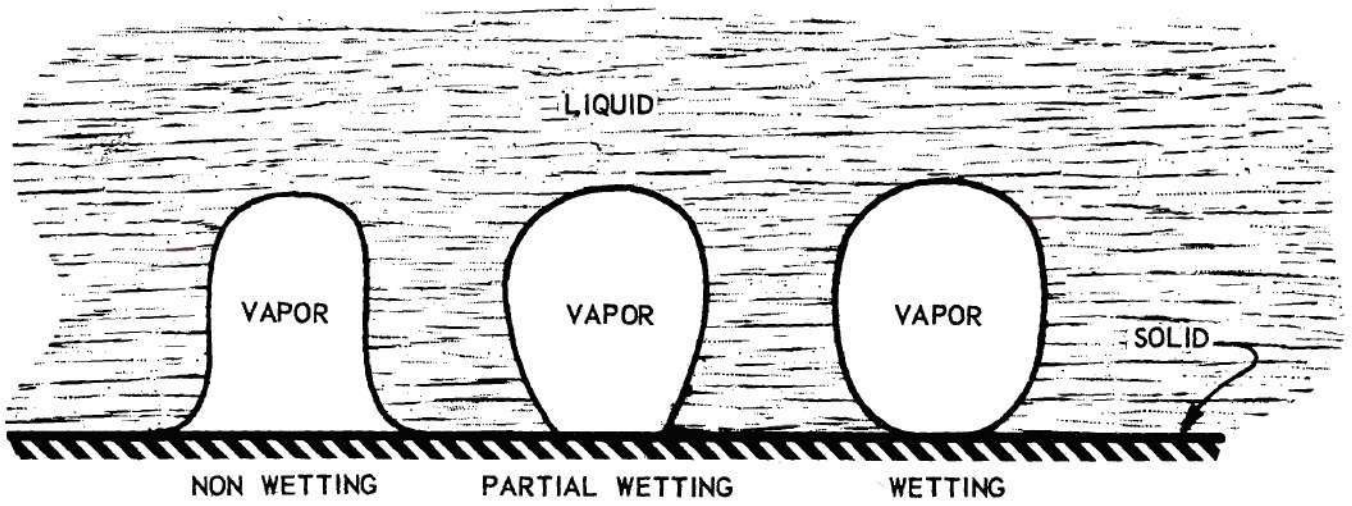
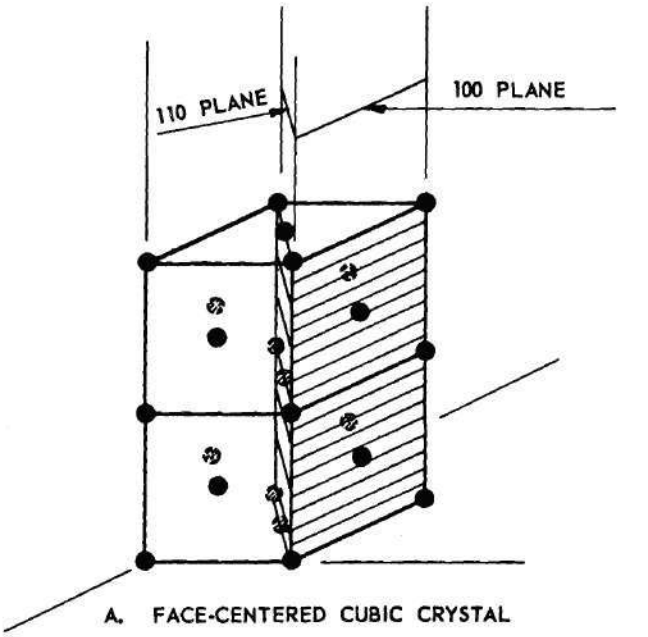
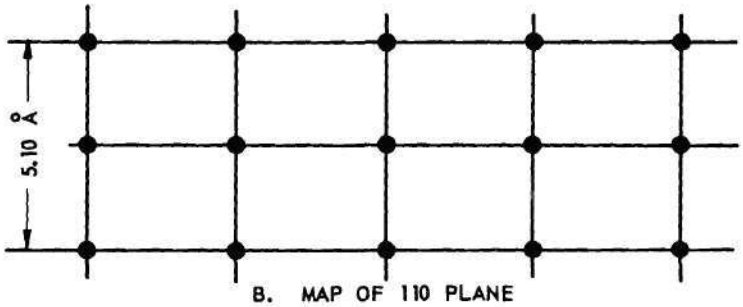


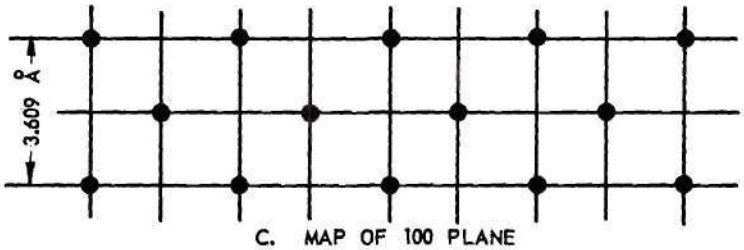
Figure 2. Vapor-Liquid-Solid Interface Relationship With Wetting (From Jakob).



A. FACE-CENTERED CUBIC CRYSTAL



B. MAP OF 110 PLANE
(9.2 Å^2 Per Atom)



C. MAP OF 100 PLANE
(6.5 Å^2 Per Atom)

Figure 3. Details of Copper Single Crystal.

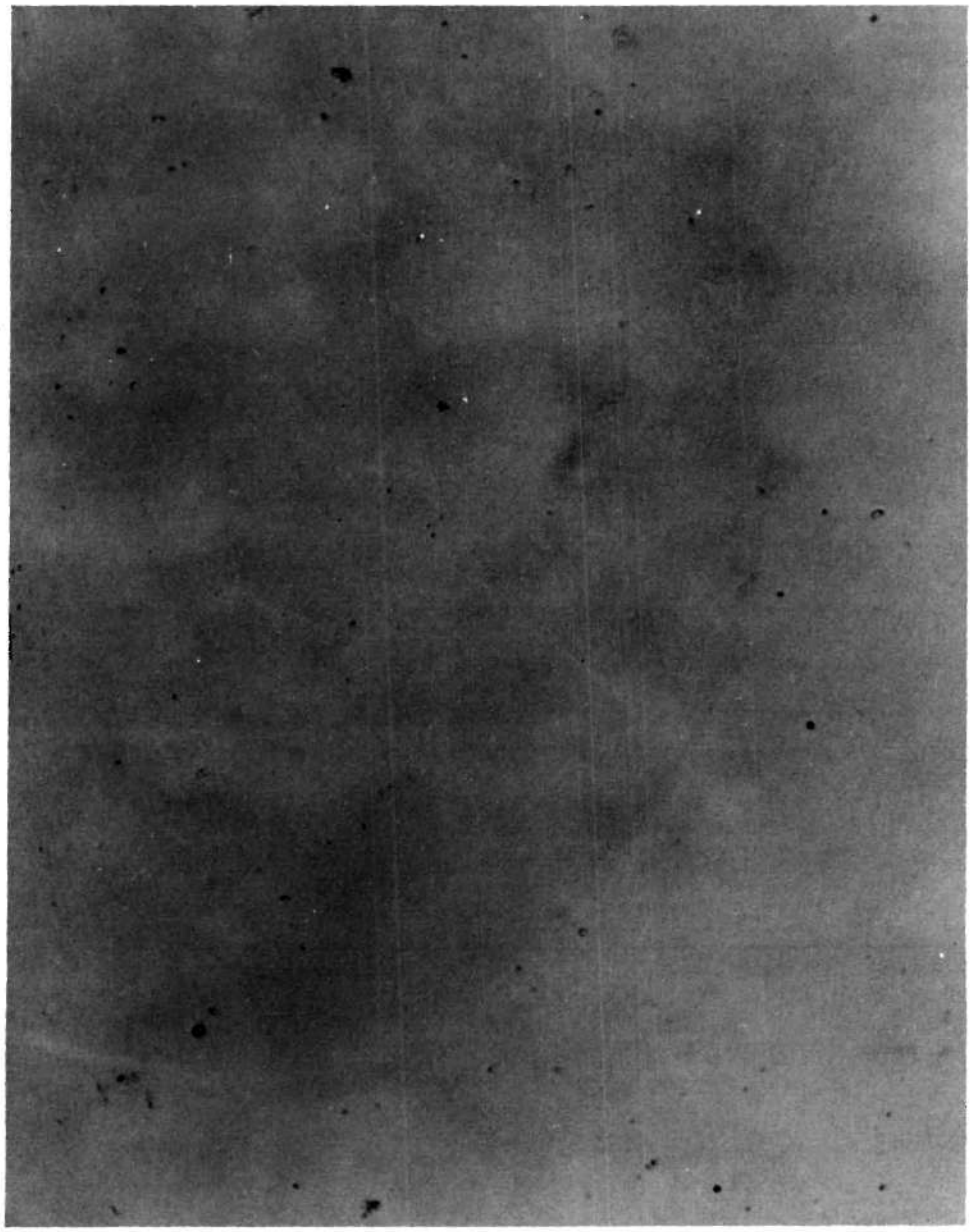


Figure 4. 110 Crystal Surface After Electrolytic Polishing. (570X)

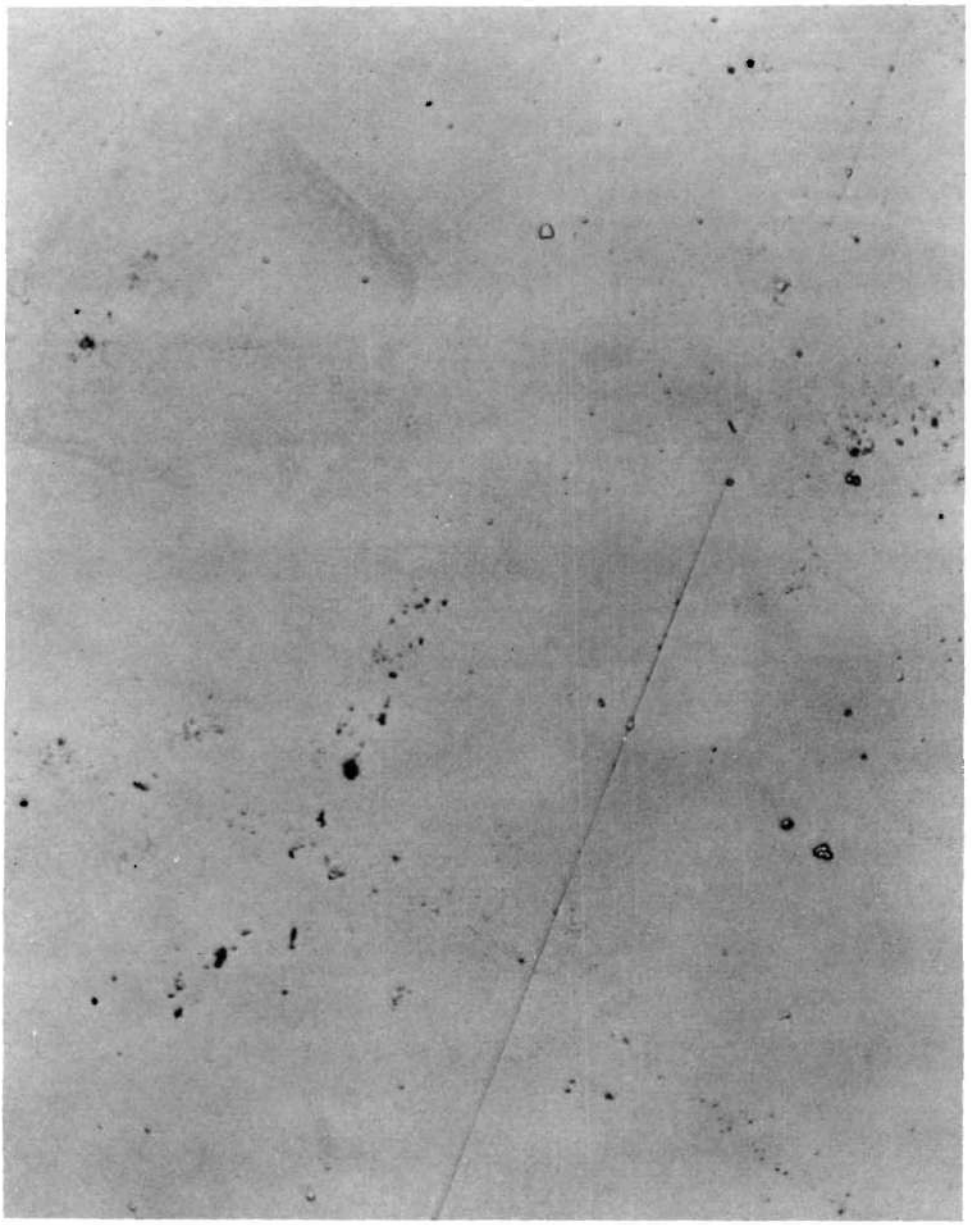


Figure 5. 100 Crystal Surface After Electrolytic Polishing. (570X)

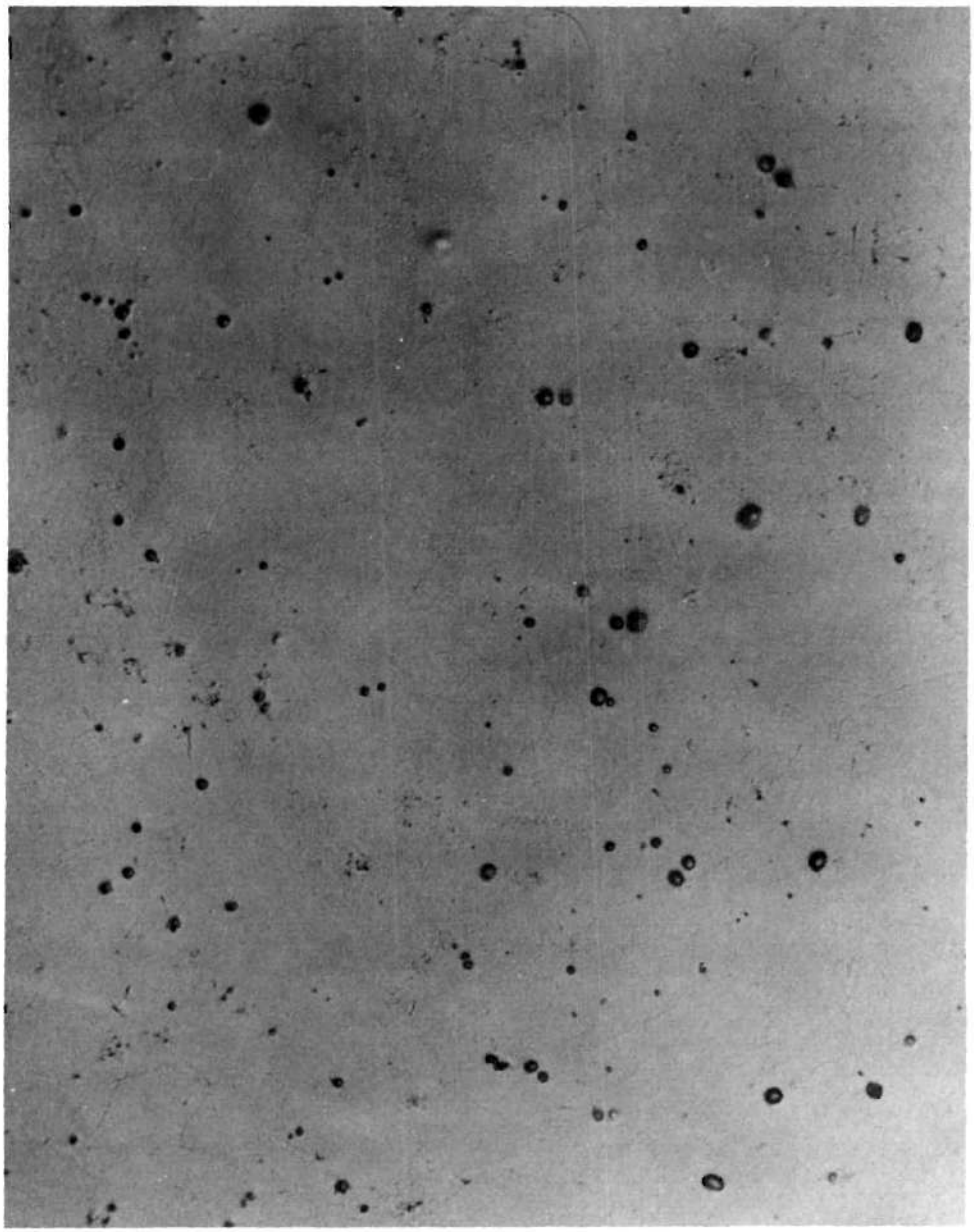


Figure 6. Polycrystalline Surface After Electrolytic Polishing. (570X)

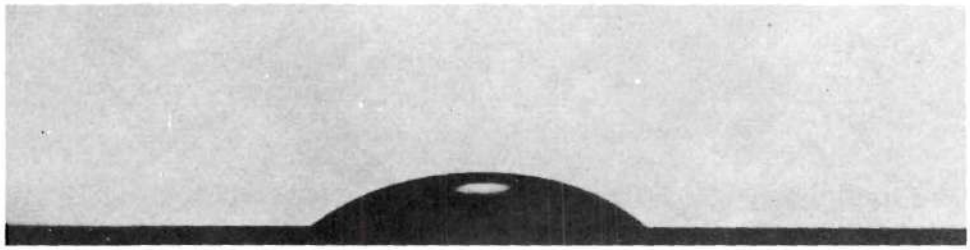


Figure 7. Fresh Stearic Acid on 110 Crystal.

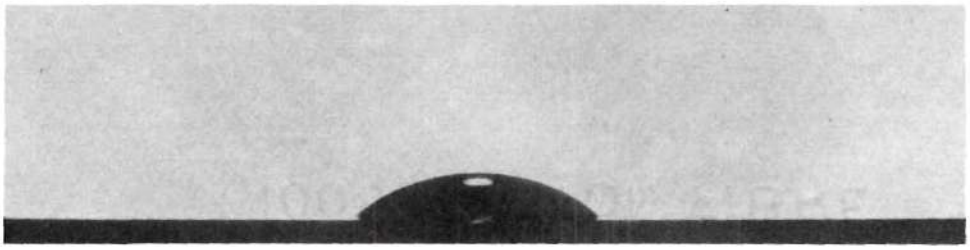


Figure 8. Fresh Stearic Acid on 100 Crystal.

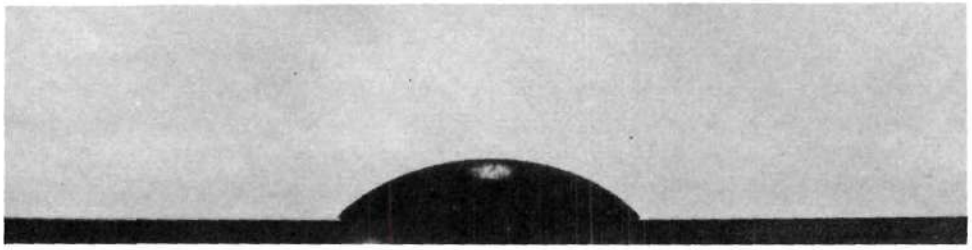


Figure 9. Fresh Stearic Acid on Polycrystal.

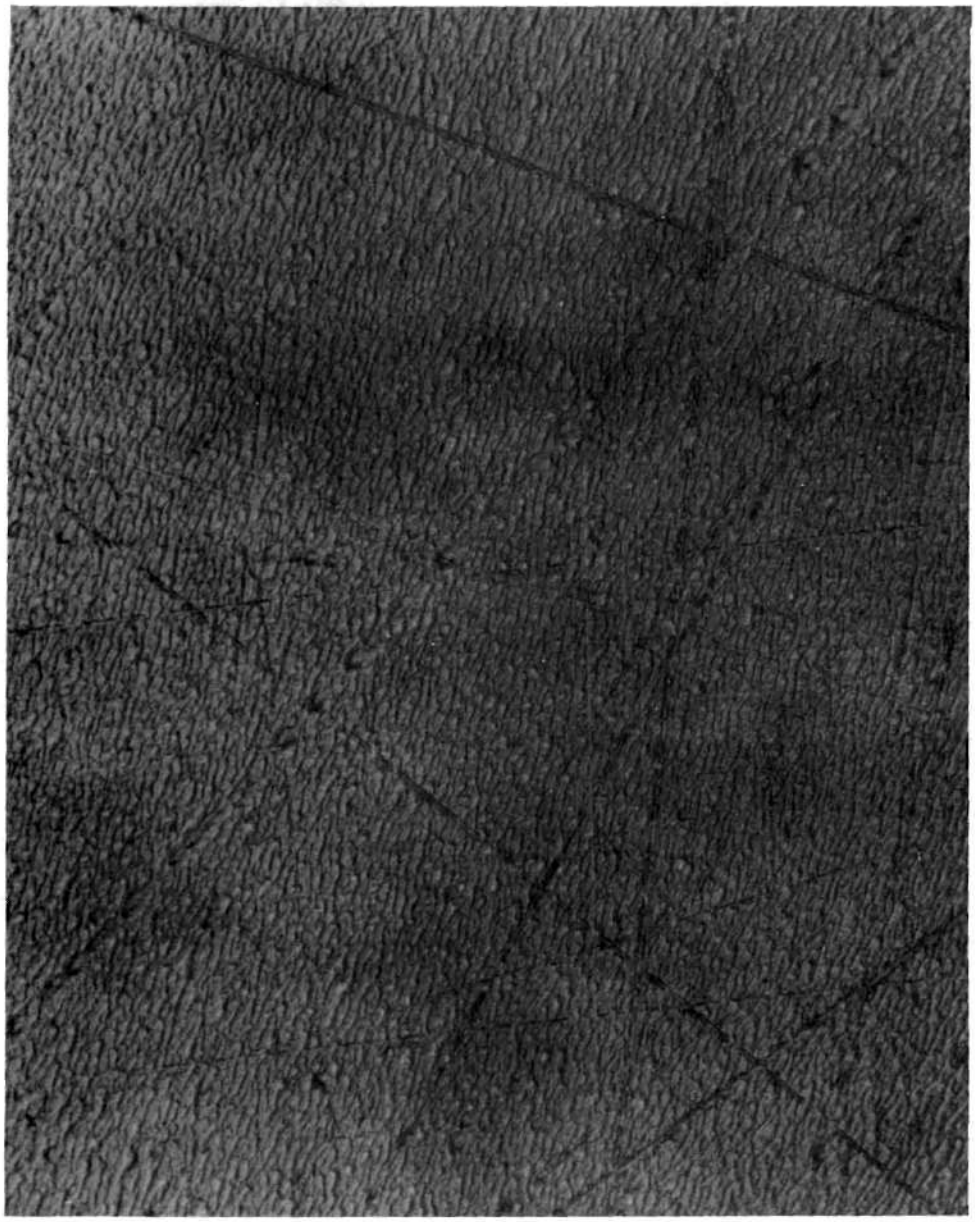


Figure 10. 110 Crystal Surface After 6 Hours Immersion in 170°C Stearic Acid. (570X)

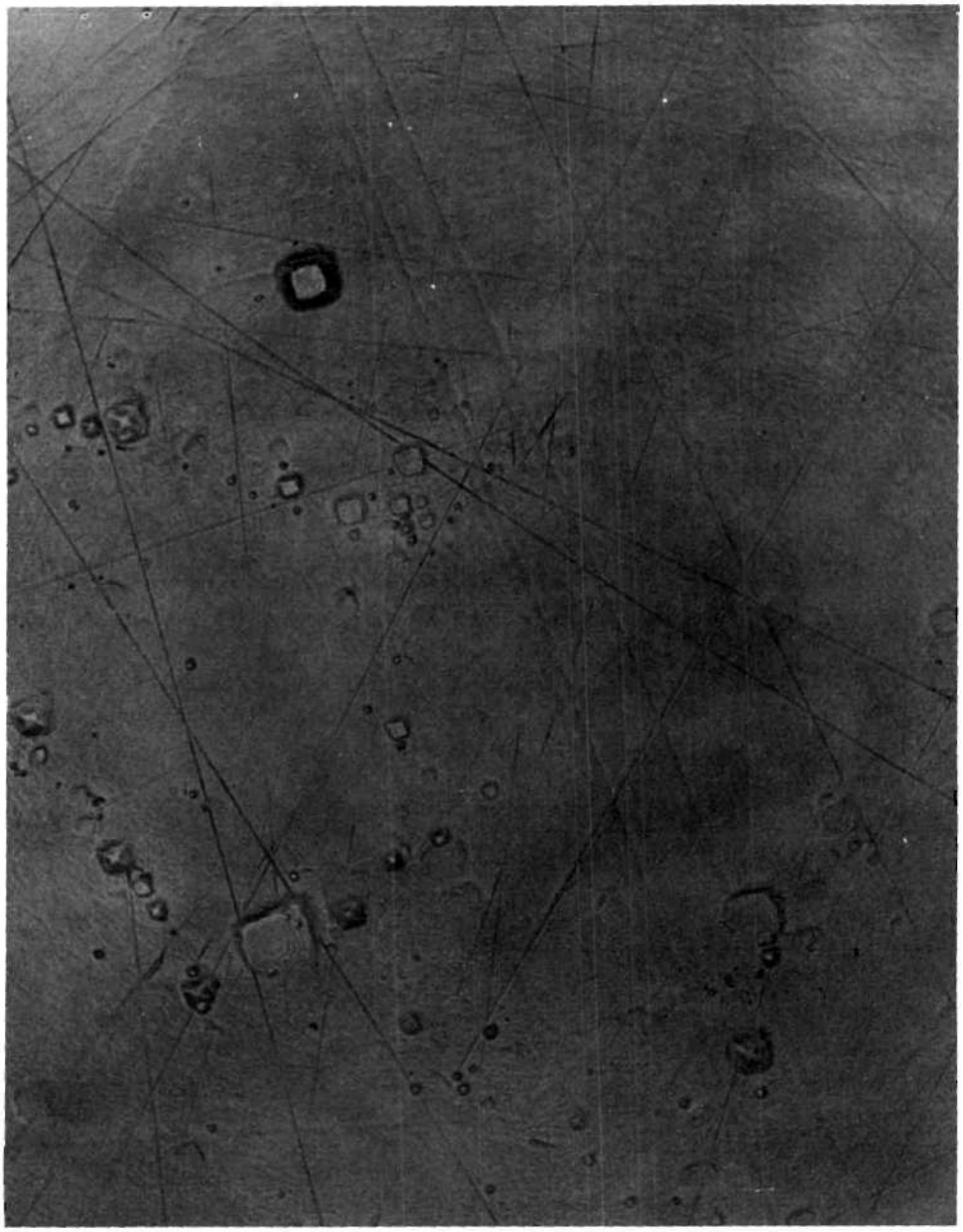


Figure 11. 100 Crystal Surface After 6 Hours Immersion in 170°C Stearic Acid. (570X)

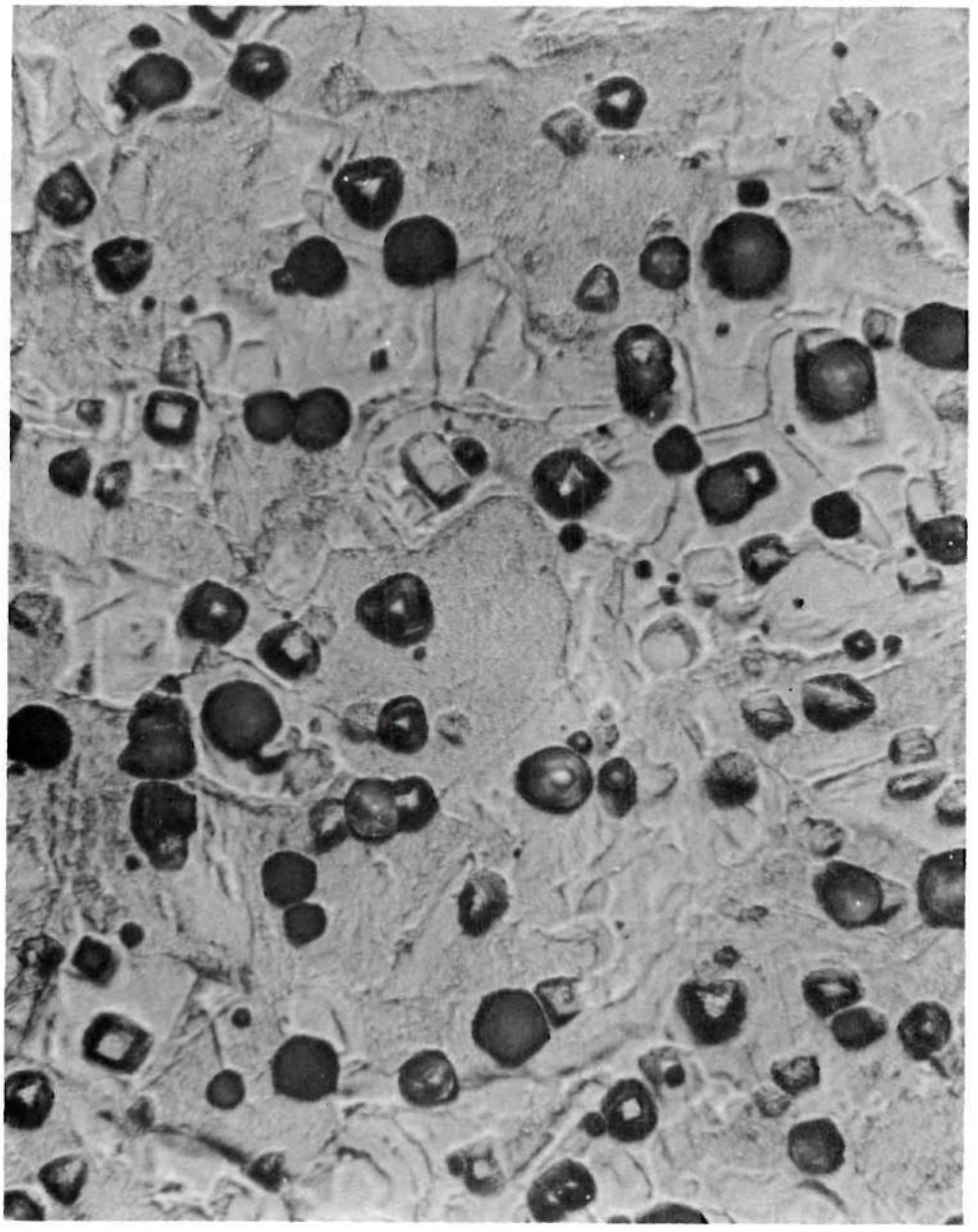


Figure 12. Polycrystalline Surface After 6 Hours Immersion in 170°C Stearic Acid. (570X)

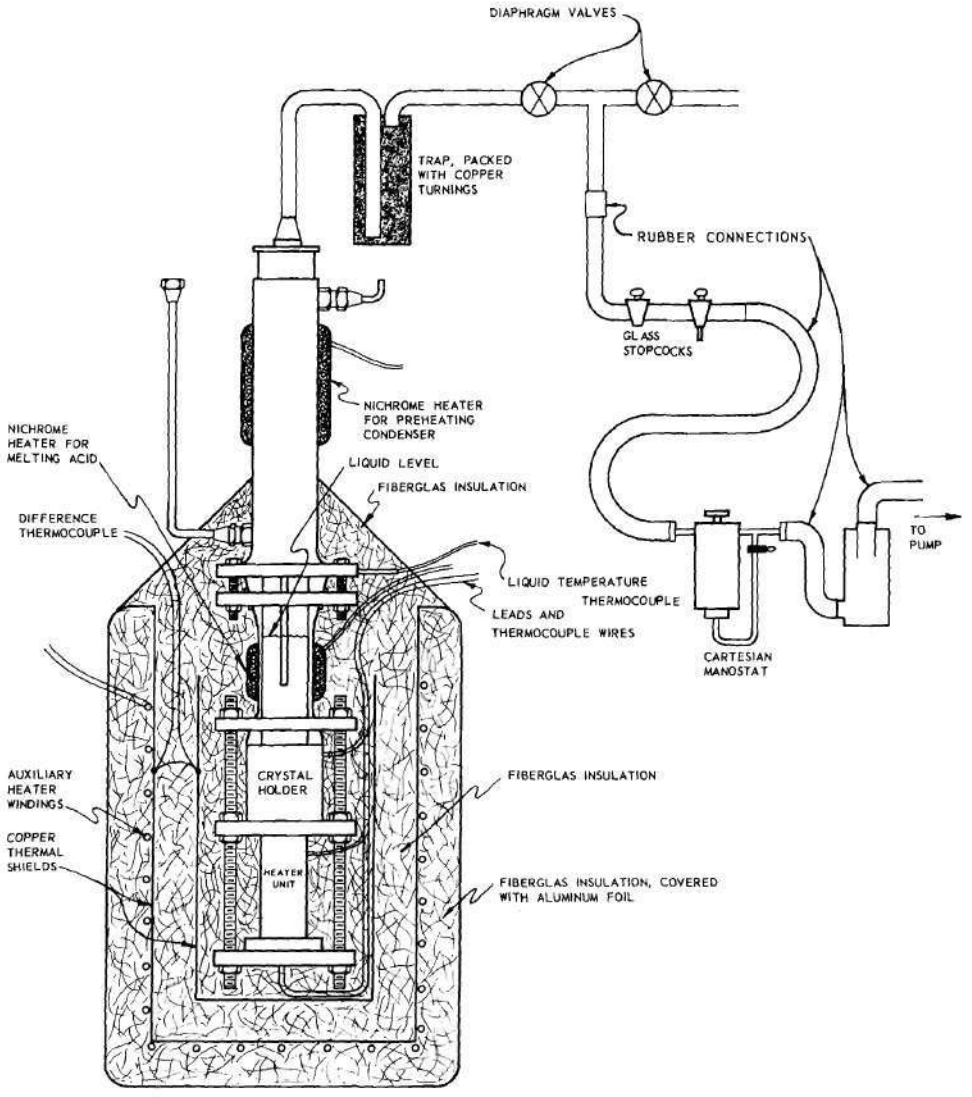


Figure 13. Boiler and Vacuum System.

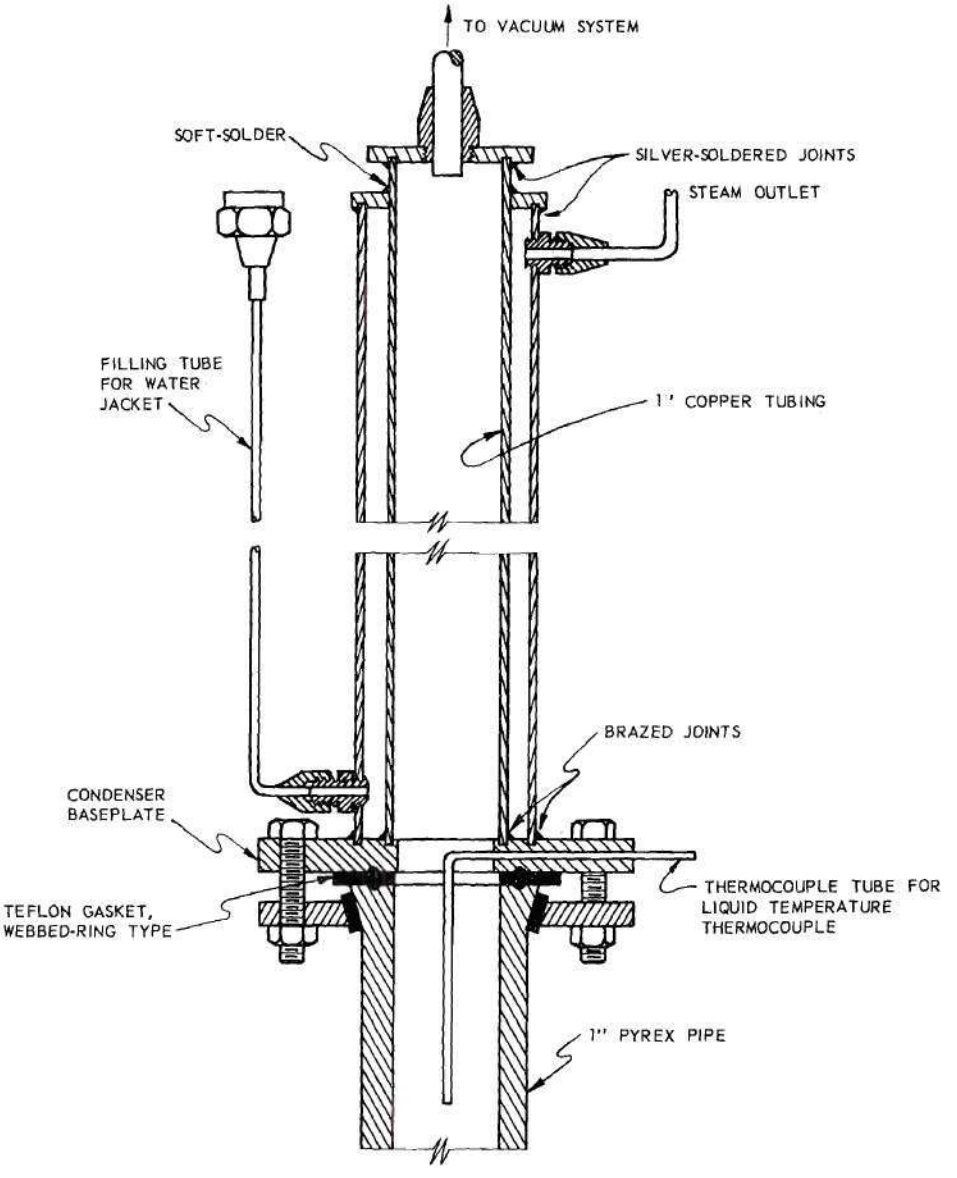


Figure 14. Condenser Details.

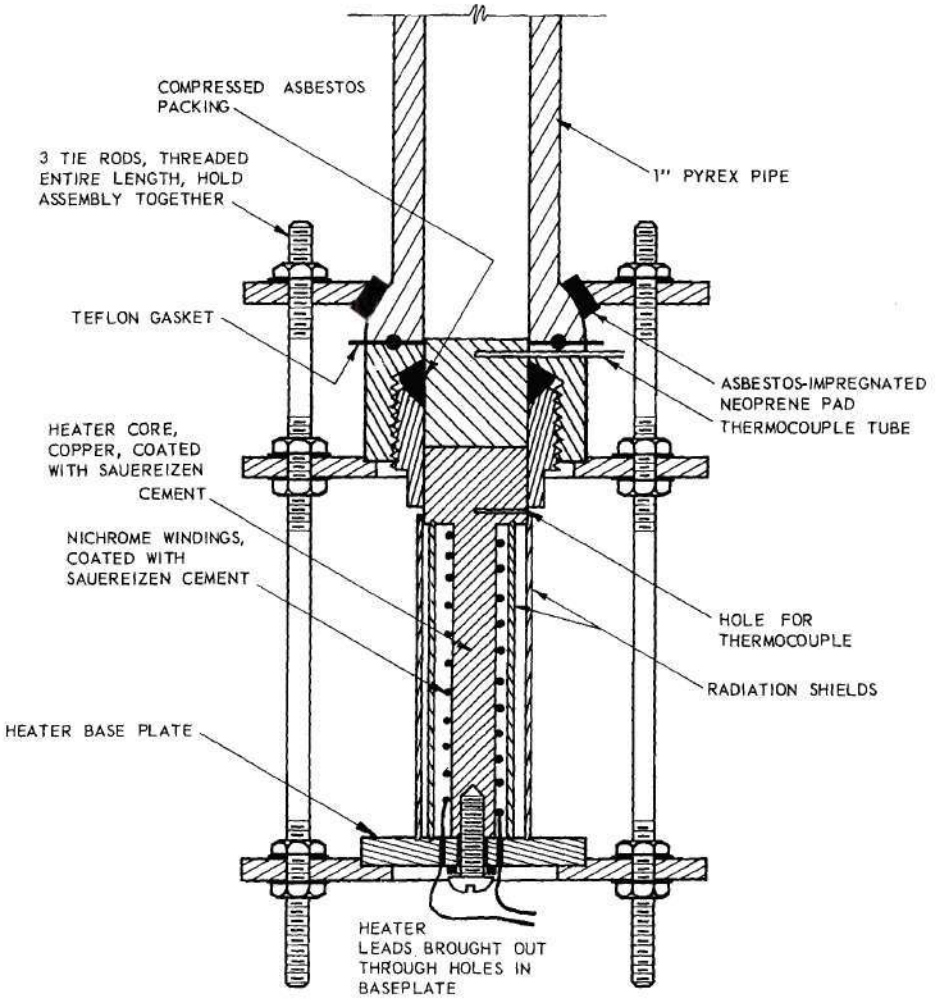


Figure 15. Heater Assembly.

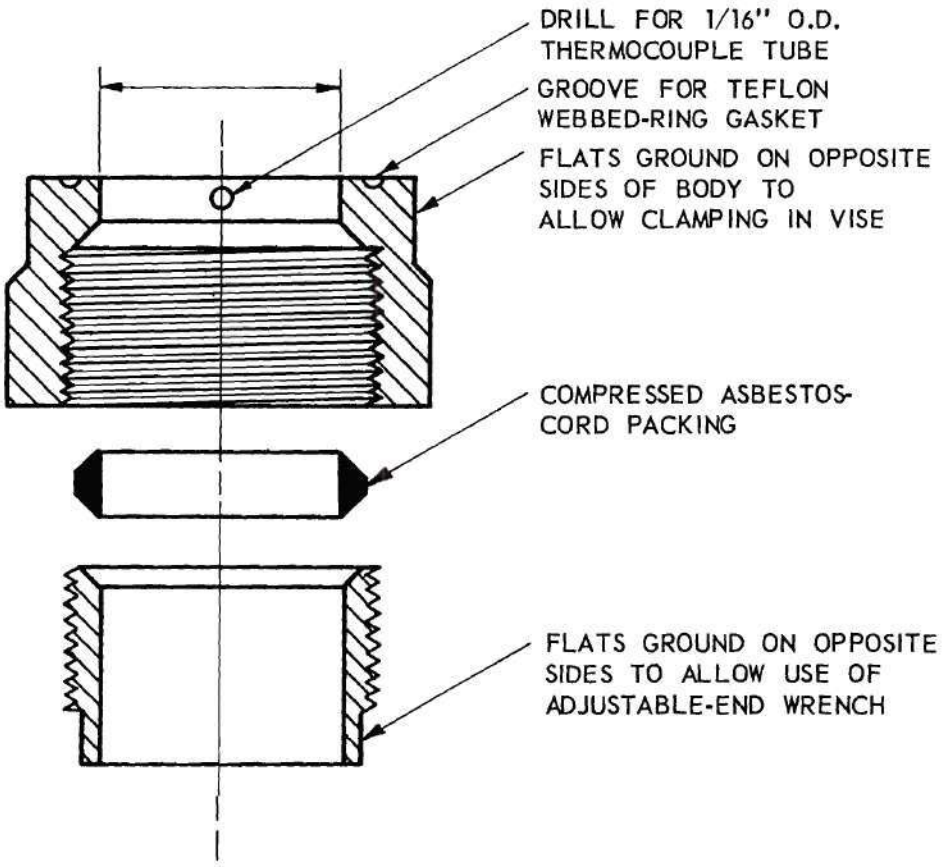


Figure 16. Crystal Holder.

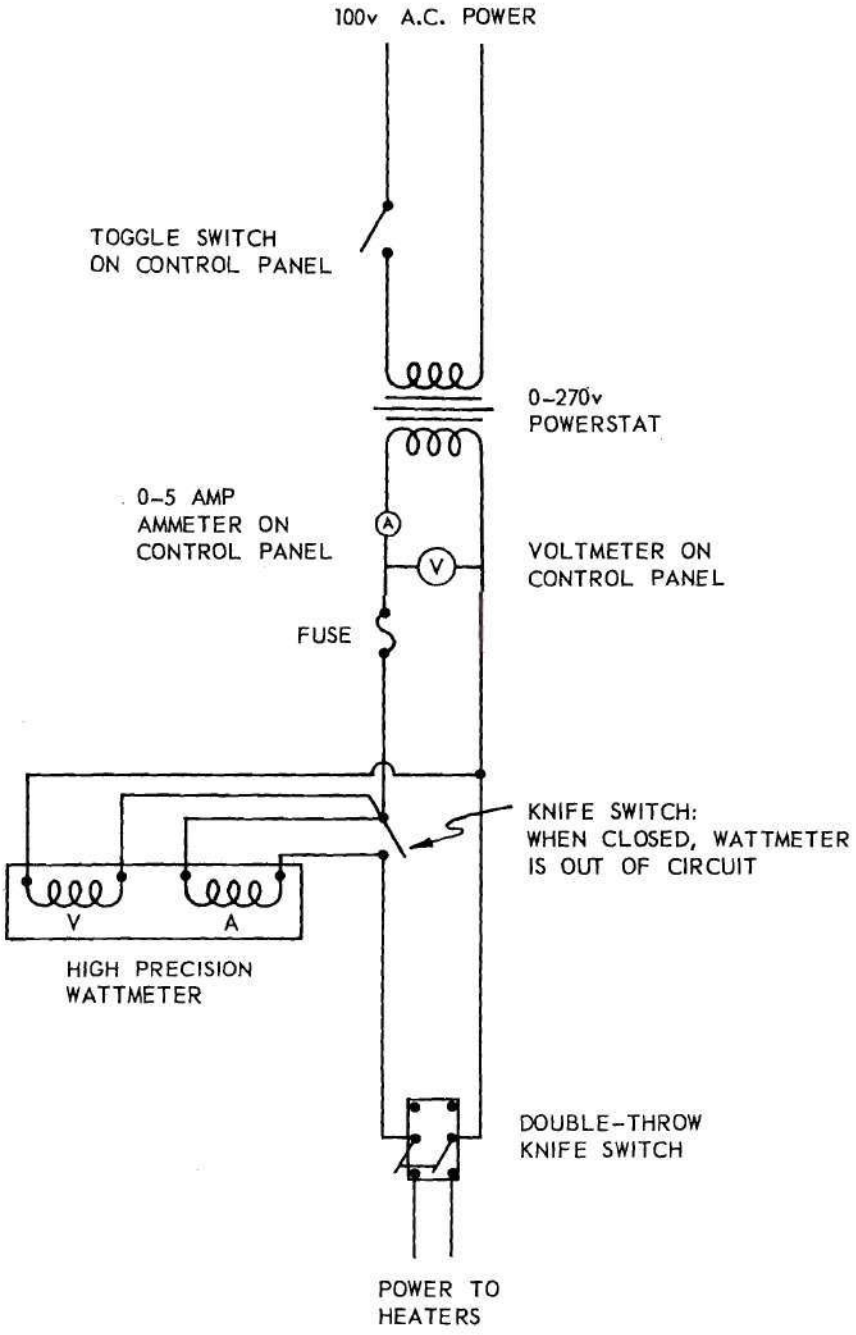


Figure 17. Power Supply Circuit.

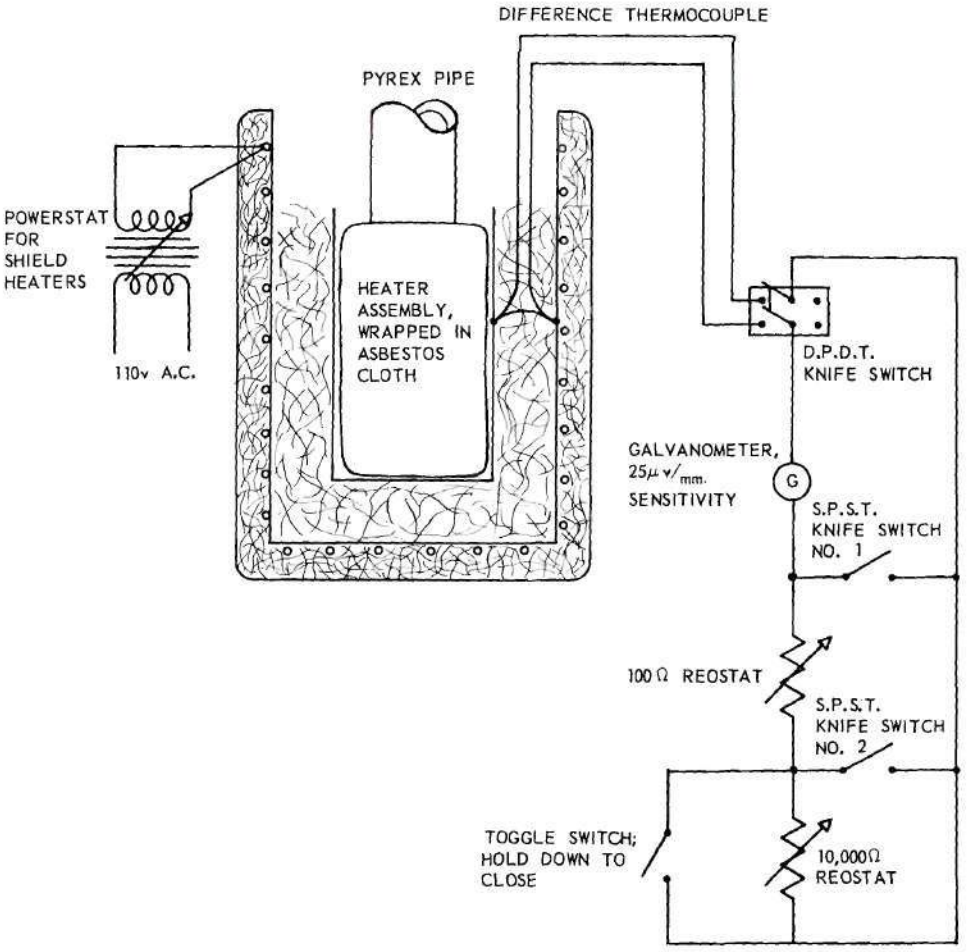


Figure 18. Temperature Indicating System for Thermal Shields.

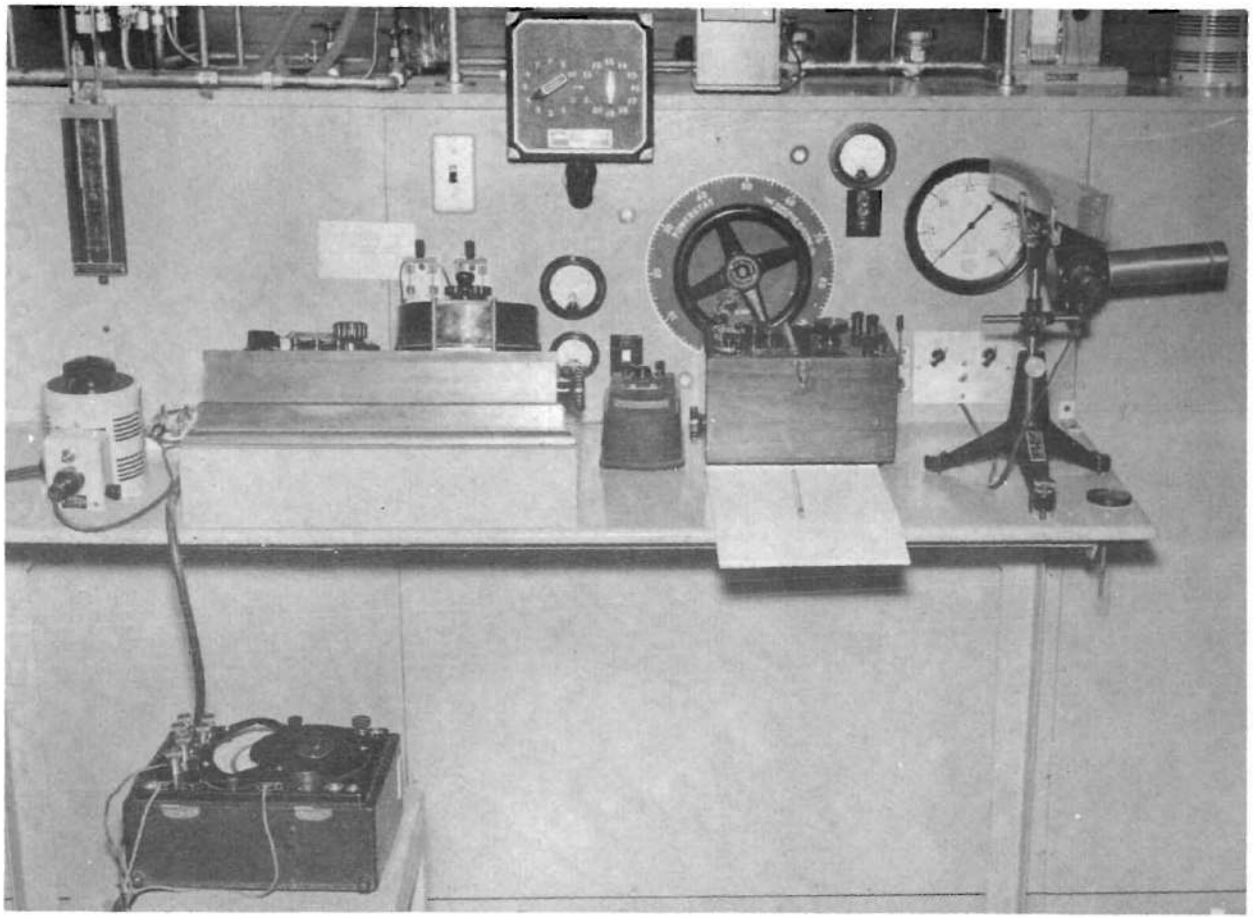


Figure 19. Instrument Panel for Main Boiler System.

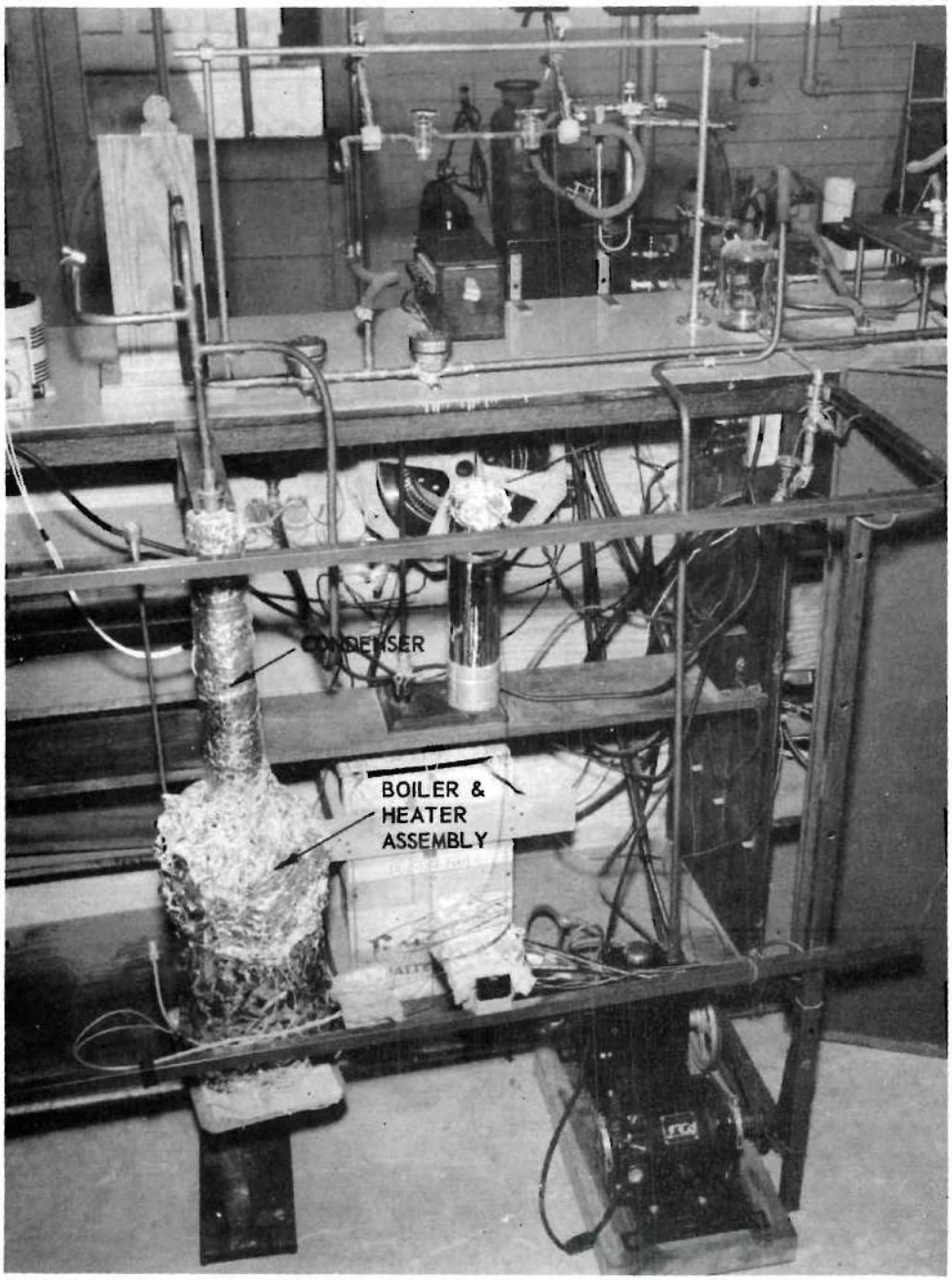


Figure 20. View of Main Boiler System.

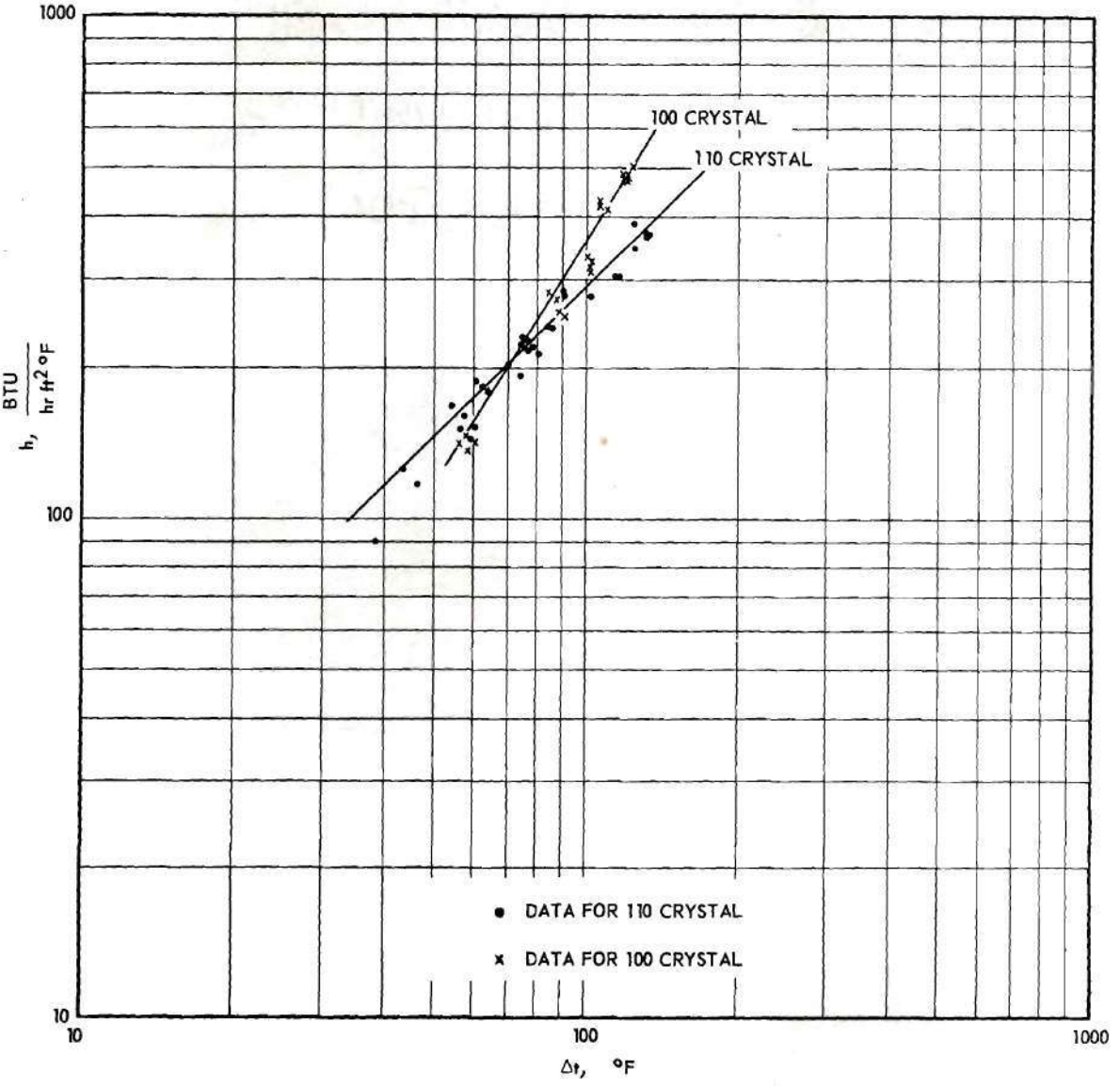


Figure 21. Data for Boiling Stearic Acid on Copper Single Crystals.

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VITA

The author, Zelvin Levine, is the son of the late Hyman and Lena Levine, each of whom came to the United States from Russia before World War I. Zelvin, the youngest of four children, was born in Savannah, Georgia, June 7, 1930. During the period 1932 - 1940, he lived in the small town of Estill, South Carolina, where he completed the first five grades of elementary school.

In 1940 the author's father returned to his original occupation, that of a painting contractor, in Savannah. At this time the author entered the Charles Ellis Grammar School. Subsequently he attended Richard Arnold Junior High School and Savannah High School. He was graduated with a diploma in the scientific option, June 1947.

In September 1947 the author started what was to be a long association with the Georgia Institute of Technology. He received the Bachelor of Chemical Engineering degree, designated with highest honor, in June 1951.

On March 16, 1951, the author married Carolyn Fluke of Savannah, Georgia. Their first child, Michael Neil, was born March 15, 1952, in Oak Ridge, Tennessee. Their younger boy, Howard Lee, was born May 19, 1955, in Atlanta. His birth came less than one day after the author completed the last of his comprehensive examinations in Chemical Engineering.

Having been selected as a "category A student" by the staff of the Oak Ridge National Laboratory, the author moved to Tennessee for advanced study at the Oak Ridge School of Reactor Technology. In August of 1952, after twelve months of full-time study, the author received a diploma in recognition of satisfactory completion of the prescribed courses. Although the Oak Ridge School of Reactor Technology is not a degree-granting institution, the graduates were granted the distinguished title, "Doctor of Pile Engineering."

Following the year of study in Oak Ridge, the author returned to the Georgia Institute of Technology, where he was awarded the Humble Oil Company Fellowship for two years of study. Entering the Graduate Division, School of Chemical Engineering, he started his graduate studies in September of 1952. Having decided to specialize in the Nuclear Engineering field, the author concentrated his studies in the fields of Thermodynamics, Heat Transmission, and Fluid Mechanics. His minor field of study was Applied Mathematics. The author devoted three years to study on the campus, leaving when the experimental work connected with his research was completed. For the final year of study, the author was awarded a National Science Foundation Fellowship.

In September 1955, the author moved to Akron, Ohio, where he joined the Atomic Energy Division of the Babcock and Wilcox Company as a Nuclear Engineer. He is now located in Lynchburg, Virginia with the divisions' Reactor Design Section.